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A Knowledge-Based System To Aid In The Fatigue Design Of Steel Bridges

by

Matthew Allan Bunner

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Advisor John L. Wilson Date 19 June 1990
Dr. John L. Wilson

Chairman Date 19 June 1990
Dr. Irwin J. Kugelman

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Abstract

This thesis presents the development and implementation of a knowledge-based system (KBS) for advising bridge designers on the concepts of fatigue and its effect on proposed qualitative bridge designs. The domain addressed, fatigue damage in bridges, is a major, worldwide infrastructure problem.

This work looks at the rationale behind the development of the system, analyzes the formalization of the knowledge within the domain, and describes the approach taken for the computer implementation of the system. In addition, the integration of the system into a comprehensive open-system model in the domain is covered.

The system provides the user, either a student or a bridge designer, with commentary and recommendations on the selection of general bridge characteristics and the selection of a topology and connectivity of individual bridge details, as it steps through the generation of a preliminary, qualitative bridge design with him. The system is intended to act as a stand-by advisor on fatigue in the absence of a human expert, but also serves as a teaching tool by presenting information in a tutorial fashion. By performing these functions, the system aids in the dissemination of expert knowledge, so that it can be applied to the solution of practical real-world problems.

The implemented KBS, called the Fatigue Design Consultant (FDC), is tested on a number of bridge designs, and the results are analyzed for consistency and usefulness. In addition, possible system extensions and enhancements, which are intended to increase the effectiveness of FDC are presented.

1. Introduction

1.1 Thesis Objectives

This research project has two primary objectives. The first objective is to develop a prototype knowledge-based computer system to aid in the generation of bridge designs that are resistant to the causes of fatigue damage. The second objective is to extend and verify particular concepts in the field of knowledge formalization.

The Fatigue Design Consultant (FDC), as developed, is intended to serve as a surrogate consultant, or stand-by advisor, to transfer expert knowledge in the field of fatigue and fracture of steel bridges to the practicing bridge designer in a professional environment, or to the student of bridge design in an educational environment. Specifically, FDC provides commentary and recommendations on both generic bridge parameters and on individual detail design as it steps through a preliminary qualitative design process with the user. This operation serves the dual function of facilitating the development of fatigue-resistant bridge designs, and helping to increase the user's awareness of fatigue and the impact it can have on the performance of particular bridge details.

In addition, the development process utilized for FDC was formulated and structured in a way that a number of both new and previously developed concepts in the field of knowledge formalization could be further tested and evaluated [Wong & Wilson 89, Stabler 86, Chen 88]. These concepts were related to the system's framework (open-system model), the knowledge representation scheme, and the form and method of the knowledge presentation and transferal to the user [Chen 88].

1.2 Background

1.2.1 The Problem

One of the most severe problems facing civil engineers and society is that of a worldwide decaying infrastructure. This problem is quite apparent in the condition of structural distress that exists in a large portion of the bridges in the United States. "Of 574,000 inventoried highway bridges in the United States, 260,000 of them (45%) are classified as structurally deficient or functionally obsolete" [HBRRP 85]. While there are numerous causes which contribute to the deterioration of these structures, it has been determined that a major cause of the distress in steel bridges is fatigue, the cumulative effect of repetitive live loads [Fisher 84].

Current bridge codes attempt to address the fatigue problem by classifying design details according to their fatigue susceptibility and then limiting these details to prescribed fatigue stress ranges. An example of this practice can be seen in the current American Association of State Highway and Transportation Officials (AASHTO) Standard Specifications for Highway Bridges (Fourteenth edition, section 10.3). These design provisions, however, do not take into account fatigue damage initiating from large preexisting cracks or arising from a condition of out-of-plane distortion [Fisher 84].

A large number of steel bridges have experienced fatigue cracking due to out-of-plane distortion (distortion-induced fatigue). Appendix A lists the types of design details at which cracking has been observed in steel bridges. It can be seen from reviewing this list that a large percentage of the observed cracking (roughly 50%) is attributed to a condition of out-of-plane distortion which existed on the bridge. In addition, a smaller, yet significant portion of the observed cracking was determined to have initiated from an initial imperfection. Therefore, while the current design provisions address the fatigue susceptibility of certain bridge details based on their classification, other details that meet the restrictions imposed by the codes may still experience fatigue cracking from these "overlooked" causes.

Since, only a relatively small amount of in-service data on distortion-induced fatigue and fatigue from other various sources has been collected, it is difficult to codify guidelines which adequately confront the problem. The information which has been collected is concentrated in the hands of a small number of experts in the field of fatigue and fracture of bridges and remains formalized only in heuristic guidelines and rules-of-thumb. This being the case, bridge designers, unfamiliar with these concepts and bound only by the restrictions imposed by the codes, are likely to generate bridge designs that have details which are susceptible to fatigue damage. This problem is compounded by the fact that the actual detailing on a bridge design may be "recycled" from previous bridge designs or left up to draftsmen or fabricators with even less of a knowledge for the types, causes, and consequences of fatigue.

1.2.2 The Need For FDC

Bringing the knowledge and experience-based heuristics of experts in the domain of fatigue and fracture of bridges into the bridge design process is essential if the problems associated with fatigue, specifically those not accounted for in design codes, are to be avoided. It is important that this knowledge be made readily available to bridge designers as they perform a preliminary qualitative design. This, however, is the crux of the problem. It is impractical for the experts in the field, because of their limited time and availability, to be personally involved in each and every bridge design project. It is, therefore, imperative that a better mechanism than codes be used to transfer this expert knowledge to the novice or inexperienced designer or detailer be developed.

This need provided the basis for the development of the Fatigue Design Consultant (FDC), a knowledge-based computer system intended to serve as a surrogate consultant, or stand-by advisor, for bridge design. To be used by the novice or inexperienced bridge designer or detailer, the system is intended to confront the problem of fatigue both directly, by providing expert evaluation of specific bridge designs, and indirectly, by promoting the dissemination of this critical knowledge.

1.3 Knowledge-Based Systems

1.3.1 Overview Of Knowledge-Based Systems

Knowledge-based computer systems (KBS) are a form of Artificial Intelligence (AI) intended to "Emulate aspects of intelligent problem-solving" [Chen 88]. At a minimum, a KBS consists of a knowledge base, or an organization of domain information necessary for the representation of a problem situation and possible alternative outcomes, and an inference mechanism which allows for the evaluation of case specific information to traverse through the problem-solving process and arrive at a specific outcome. In simplistic terms, the knowledge base can be viewed as general knowledge of a certain domain, and the inference mechanism as the means of reasoning about or drawing conclusions from specific information within that domain.

Knowledge-based systems differ from conventional computer programs in that a KBS utilizes symbolic processing rather than numerical processing. Further, a KBS utilizes inferencing as it steps through a series of actions (which are typically not predefined), evaluating either experience-based information and / or quantitative models to arrive at a conclusion. In contrast, a conventional computer program steps through a definitive series of algorithmic procedures to arrive at a quantitative solution. These characteristics of KBS are those which make them useful in modeling the knowledge and reasoning of human experts who often solve problems qualitatively by applying heuristics, and which cannot be represented in a quantitative, procedural format.

1.3.2 Suitability Of Knowledge-Based Systems In The Domain

The first step in producing a practical, effective knowledge-based system is first determining whether or not the problem or domain to be addressed is suitable to modeling in such a system. A partial list of criteria to assess the suitability of an application area to the KBS approach is provided below [Hendrickson and Au 89]. Based in part on this criteria, it has been determined that the task of evaluating bridge designs for fatigue considerations is well-suited to modeling in a knowledge-based system.

- There are recognized experts in the field whose performance is significantly better than that of novices.

- Tasks are primarily cognitive, requiring reasoning at multiple levels of abstraction.

- Algorithmic solutions are either impractical or result in overly constrained or specialized programs.

- There are substantial benefits possible from the knowledge-based system either through the importance of each decision made or due to the large volume of decisions to be made.

Within the domain of fatigue and fracture of bridges, specifically the design of bridges to reduce fatigue susceptibility it has been concluded that only a handful of experts exist [Chen 88]. It has been surmised that even the non-expert designers who do produce "good" bridge designs may not understand why their designs are "good". This lack of knowledge or understanding of fatigue may be attributed to the limited amount of research performed or formalized in this field, or the fact that the subject is not thoroughly covered (if covered at all) during the education or training of bridge designers.

The task of evaluating bridge designs for their susceptibility to fatigue is qualitative, with the expert's judgements often dependent on heuristics or experience. The types of recommendations or comments provided by experts are not suited to algorithmic solutions, and often must be made on different levels of abstraction, depending on the type of solution or explanation called for, or the amount of information available to the expert during a diagnosis or evaluation of a potential problem.

By aiding in the generation of bridge designs that are less susceptible to fatigue damage, a goal of FDC, substantial benefits could be reaped. From an economic viewpoint, the potential financial benefits from avoiding the fatigue-induced fracture problem in bridges has been estimated in excess of $75 million each year [Veshosky 86]. In addition, the possibility of fracture and catastrophic failure due to fatigue damage, which could result in the loss of life, could be lessened.

1.4 Incorporation Of FDC In Existing KBS Framework

1.4.1 The Bridge Fatigue Investigator

The Bridge Fatigue Investigator (BFI), developed at Lehigh University, is a knowledge-based system intended to aid in the fatigue inspection and evaluation of steel I-girder bridges, a type of bridge particularly susceptible to distortion-induced fatigue [Fisher 84]. BFI was developed to address the problem of fatigue damage in existing bridges by transferring expert knowledge in the field of fatigue and fracture, specifically the detection and repair of fatigue-critical conditions, to the practicing bridge inspector and engineer. The system arose from the need to detect fatigue cracking at an early stage of crack growth, when repair and retrofit procedures would be both effective and economical, and the fact that domain experts have, "demonstrated an often uncanny ability to discover fatigue cracks that have escaped visual detection of others" [Chen 88]. Another factor that prompted development of BFI was the fact that the relatively inexperienced and untrained corps of bridge inspectors are burdened with the overwhelming task of inspecting every bridge in the United States every two years, as mandated by the FHWA. This task would call for every inspector to cover several bridges each day, a situation which eliminated the chance of a thorough inspection of every detail on every bridge [Chen and Wilson 86].

BFI operates in two stages as shown in Figure 1.1. In a pre-inspection stage, BFI utilizes information supplied by the user on bridge characteristics (primarily dealing with the structural configuration of the bridge) to target potential fatigue-critical locations on the bridge. By performing this function, BFI aids the inspector achieve a more reliable and efficient inspection.

In the post-inspection stage, BFI interprets the observations of the fatigue-critical

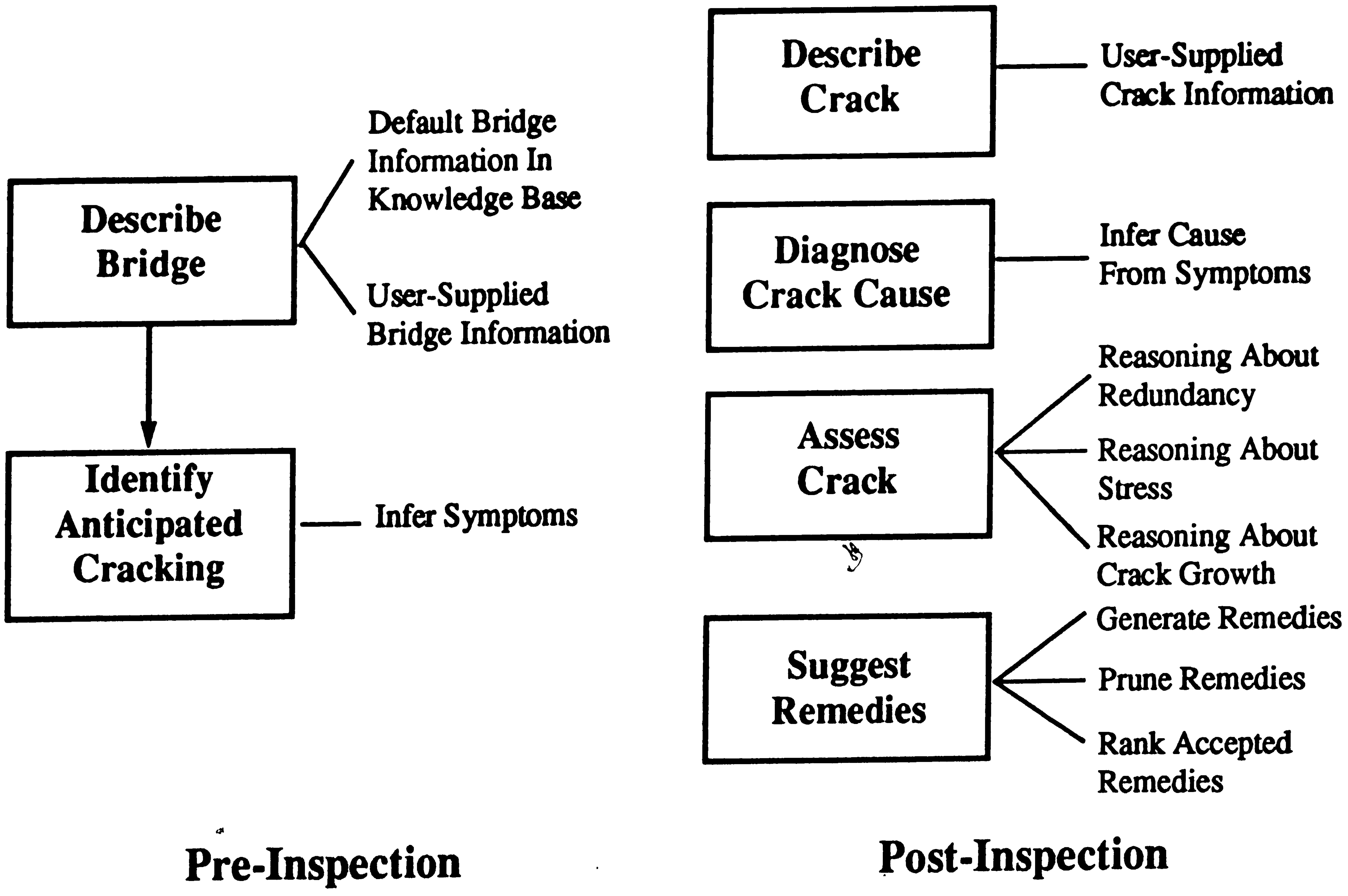


Figure 1.1 BFI Stages Of Operation

details investigated in the field, and evaluates the criticality of any cracking that is discovered. In addition, the system will suggest alternative repair or retrofit procedures that can be utilized to arrest or correct the damage. By suggesting and prioritizing suitable repair alternatives, economic and timely corrective measures can be undertaken. A complete description of the BFI system can be found in [Chen 88].

1.4.2 Open-System Model

One of the most important factors in developing a knowledge-based system which is conducive to use in real-world problems is the implementation of a system architecture which allows rapid prototyping as well as extension, expansion, and modification of the knowledge base. An open-system model developed at Lehigh University, and utilized as a framework for the BFI system, is depicted in Figure 1.2 on page 11. This architecture provides a means of organizing complex systems which are often subject to modification or extension. This type of model calls for the separation of knowledge into a core (kernel) of domain-specific knowledge, and separate scenario-related (application or task-specific) knowledge, thus allowing for multiple system applications within a particular domain. Each individual scenario can interact with the knowledge core as well as external knowledge sources (i.e. application-specific databases) through system utilities [Wong and Wilson 89].

An important characteristic of this framework is that the knowledge within the core may often not need to be modified to operate with new scenarios. If the core knowledge needs to be modified, the Knowledge Base Editor, described in Section 4.5, can be utilized to accomplish this task. Within BFI, specific scenarios are pre-inspection and post-inspection stages which operate in conjunction with the core knowledge, such as the physical configuration of the bridge and fatigue and fracture models. Thus, with the core of BFI containing domain-specific knowledge of fatigue and fracture of bridges, the development of related scenarios (other than pre-inspection and post-inspection of in-service bridges) was deemed feasible, both from a theoretical and practical viewpoint.

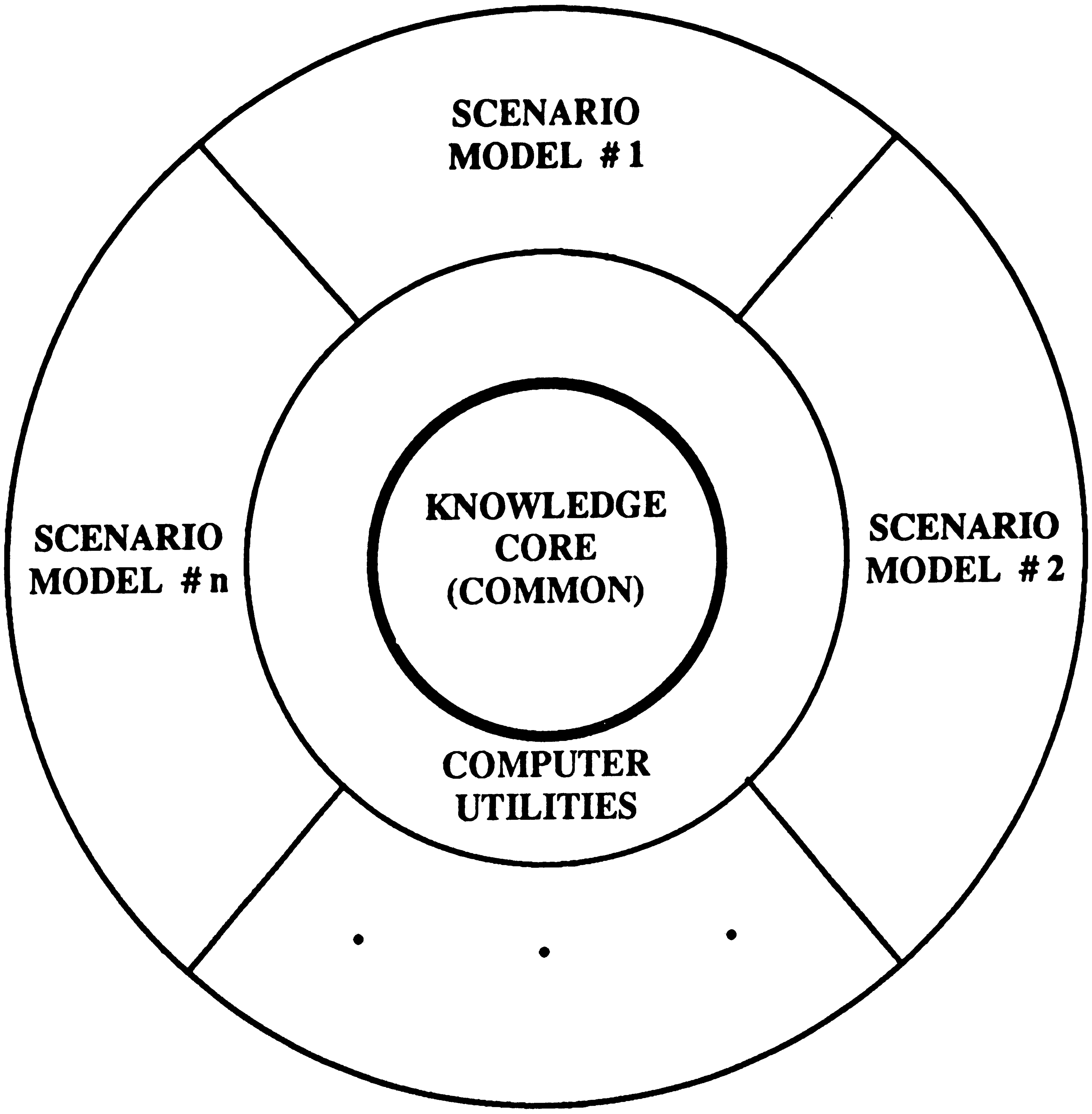


Figure 1.2
Open-System Model

1.4.3 FDC As A Scenario Module

During testing of the Bridge Fatigue Investigator with practicing bridge engineers, the consensus was that BFI was a viable tool in addressing the problem of fatigue cracking in existing bridges. In addition, it became apparent that there was a need for a tool that would help minimize the possibility of fatigue in proposed bridge designs, thus reducing the number of in-service problems. The envisioned tool would be able to evaluate proposed preliminary bridge designs for fatigue susceptibility and make recommendations as to how the design could be improved.

While BFI, in its current form, could not perform this function, the system did possess the core knowledge on bridge topology and connectivity and fatigue and fracture which was a necessity for the development of a design tool. In addition, the system was constructed using the open-system framework which theoretically would allow the development of new application-specific scenarios within the domain of fatigue and fracture of bridges. It was therefore concluded that the development of a scenario module for bridge design, the Fatigue Design Consultant, could be undertaken, and the module linked to the core of BFI. By performing this development, not only could the new tool be prototyped, but the viability of extending knowledge-based systems built on the open-system model could be studied and evaluated.

1.5 Organization Of The Remainder Of Thesis

The following chapter (Chapter 2) provides an overview of the operation of the FDC system. Chapter 3 describes the preliminary development work that was necessary to formalize both the problem to be addressed by the system and the knowledge utilized to help solve the problem, and Chapter 4 looks at the computer implementation of FDC. Chapter 5 describes the types of validation studies used to test the functionality and reliability of the system, and the results that were obtained. A discussion of the conclusions drawn from the research and development of FDC is given in Chapter 6, and Chapter 7 suggests a number of possible extensions and enhancements which are intended to increase the effectiveness of the system.

2. System Overview

This chapter provides an overview of the design and operation of the FDC system. Included in this discussion is a description of the precise portion of the bridge design process addressed, the intended usage environments for the system, and the type of results that can be obtained through use of FDC. Also discussed are a number of limitations inherent in the FDC prototype, and the potential ramifications of these limitations.

2.1 Domain And Scope Of The System

The selection of the domain and problem to be addressed by the FDC system resulted, in part, from requests made by practicing bridge engineers during testing of the Bridge Fatigue Investigator. These requests suggested that the problem of fatigue and fracture of bridges (specifically at connection details) was not being adequately addressed during the design process. This resulted in fatigue problems being encountered when the bridges were put into service. It was suggested that BFI be extended to operate in the design environment, where it could be used to help increase the designers awareness of the type of fatigue problems that could result from the selection of fatigue-susceptible details. This would be accomplished by imparting expert knowledge in the domain of fatigue and fracture of bridges, and how fatigue considerations should affect the design of bridge components and details, to the practicing bridge designer. The portion of the overall BFI system that was developed to operate in the design environment is the FDC system.

It was determined that attempting to address the entire bridge design process, including the quantitative design of components and connections, was beyond the scope of FDC. Much of the quantitative design of a structure is unrelated to its fatigue performance [Fisher 84 & 90]. In addition, including the quantitative portions of design in the scope of FDC would mandate broad extensions of the BFI core knowledge, which was not feasible for this research. These extensions would have included procedural attachments, which are numerical algorithms called by the system to perform calculations (i.e. structural analysis routines), along with structural databases for the sizing of members and connections. It, therefore, became necessary to isolate the portion of the bridge design process, apart from complete quantitative design, that would be addressed by FDC.

It was decided that the FDC prototype would look at a bounded yet representative portion of the bridge design process that encompasses both the choice of general bridge parameters, such as the layout of the bridge, and the selection and qualitative design (types of components and connections to be utilized) of bridge details. These factors are critical to the fatigue performance of the structure, and their selection is often underemphasized in conventional design procedures. The selection of general bridge parameters (Table 2.1 on page 16) is often influenced or constrained by non-structural factors. For example, the bridge layout may be constrained by the topology of the land around the structure or by geotechnical considerations. Even if the designer has little freedom in the selection of these general parameters, it is important for him to understand how these parameters will affect the selection of bridge details and their fatigue performance. The design of bridge details is often performed as an afterthought, with little attention paid to how these details will perform in service. Since the majority of fatigue damage and failures occur at connection details [Fisher 84], it

Table 2.1
General Bridge Parameters Considered In FDC

- Bridge Layout
- Span Type
- Deck Action
- Number of Main Girders
- Span Length
- Average Daily Truck Traffic
- Use of Multiple Configurations

is important that more consideration be paid to the design of these details.

FDC focuses on the design of steel I-girder bridges, a type of bridge particularly susceptible to distortion-induced fatigue. The system was developed to target these type of bridges for a number of reasons. First, since they are prone to the types of fatigue problems not covered in codes or textbooks, their design is a suitable application for FDC. Next, they comprise a large percentage of the bridges in the United States highway system. Finally, by being geared to this type of structure, FDC could more easily be implemented as a scenario module of the BFI system.

FDC acts as a surrogate consultant (stand-by advisor) to the bridge designer, as a qualitative design is formulated. It is important to stress that the system is only an advisor to be utilized as a tool by the human designer (user). While the system provides commentary and recommendations to the user at different stages of the design, the ultimate decisions, whether to accept or reject FDC's recommendations, are left in the hands of the user. By performing in this fashion, FDC accomplishes a number of goals. With the capability of accepting or rejecting the system's recommendations, the user can develop a design for situations in which he is constrained to make specific decisions. For example, if FDC recommends that a specific connection be made by bolting, but the designer is constrained to choose welding due to fabrication considerations, he can reject FDC's recommendation and select welding. He can then see how these selections may affect the performance of the structure. Also, the user can take alternative paths through the qualitative design (by making different combinations of selections), and learn what ramifications (both positive and negative) may result from the decisions he has made. Finally, by not making irrevocable decisions for the user, the system creates an environment which is much more conducive to his learning of the concepts of fatigue and how they may affect a proposed design.

The operation of FDC occurs in a number of stages. These stages, along with the type of input needed from the user and the output provided by the system, are depicted in Figure 2.1 on page 18. In the first stage (Stage I), the user answers questions about general bridge parameters (macro-parameters). The system responds with commentary on how these selected parameters interact to affect the fatigue performance of the structure, or how they may affect the performance of specific bridge details that will be designed at a later stage. The system then provides the user with the opportunity to modify his selections and, if changes are made, automatically re-evaluates the information and updates its commentary. Once the user is satisfied with his selections of macro-parameters, he can begin the qualitative design of specific details to be used on the bridge (Stage II). In this stage of operation, the user is prompted for information on the topology and connectivity of each particular bridge detail being designed. After each selection is made by the user, FDC evaluates the information currently in the knowledge base, and dynamically generates the positive and negative aspects of the user's selection, and recommends the most fatigue-resistant alternative. Once the user has stepped through the qualitative detail design with FDC, he can view a graphical display of the structure, generated from the specific information entered for the bridge being evaluated, and review a listing of all the information that was entered into the system or that the system inferred (Stage III). By being given this option, the user can check the accuracy of the information, and whether or not this information was faithfully represented by the system.

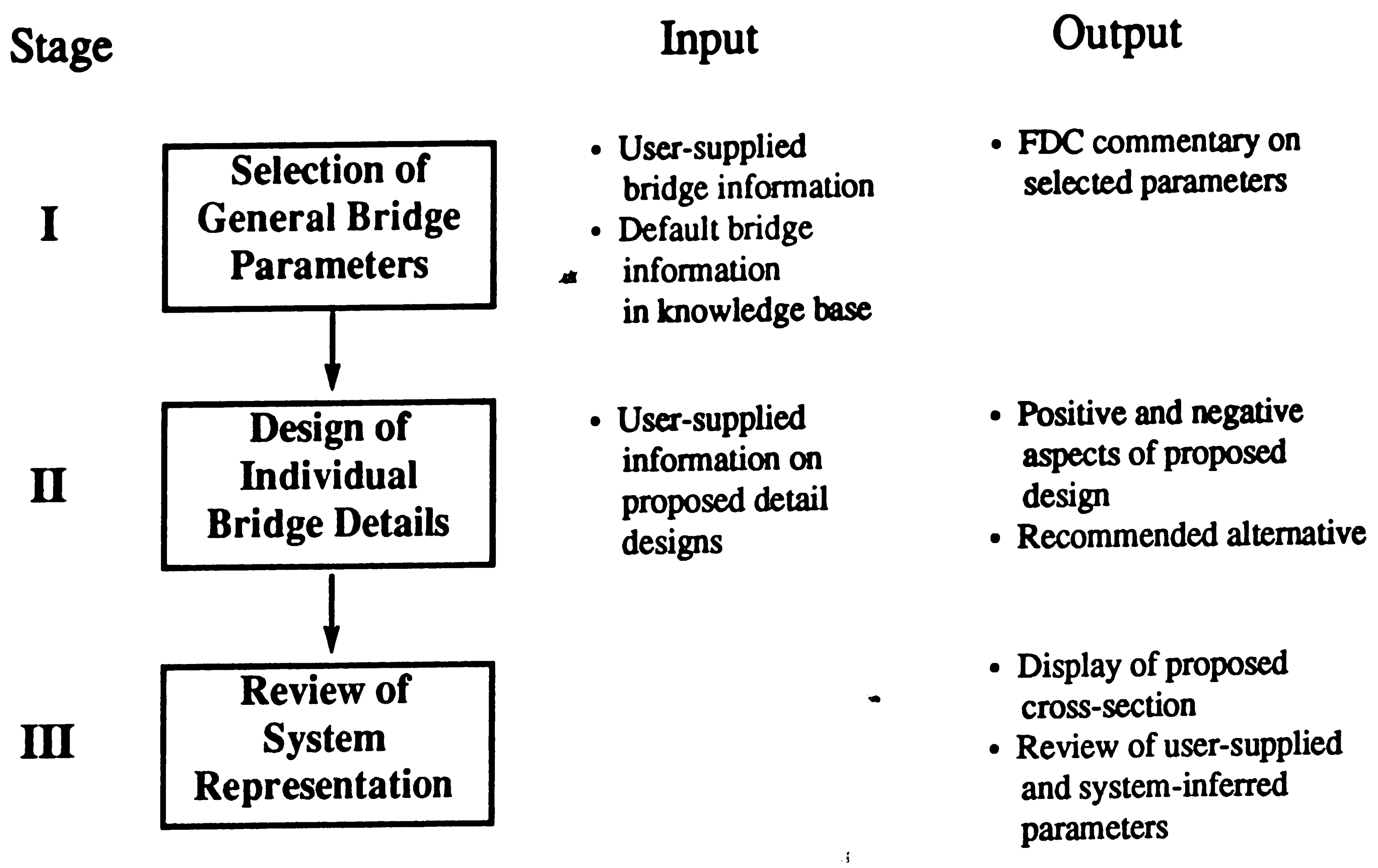


Figure 2.1
FDC Stages Of Operation

2.2 Intended Usage

The Fatigue Design Consultant is intended to be used in two different types of operating environments. The system is intended to be utilized in a professional environment by the practicing bridge designer. In this capacity, FDC serves as a tool for the inexperienced bridge designer as a qualitative preliminary design is prepared. In an educational environment, FDC can be used by a student of bridge design. Here, FDC would help teach the concepts of fatigue and how they can affect the performance of bridges. By performing this function, the system can help prepare new bridge designers for their role in practice.

At its present stage of development, the FDC prototype provides commentary and recommendations on a level geared for those with an understanding of the principles of structural engineering and bridge design. While a basic knowledge of the concepts of fatigue would be an advantage to the user of the system, FDC attempts to present its commentary and recommendations in a form that helps teach these concepts and explain how they can affect bridge performance. Chapter 5 provides two representative examples of the operation of FDC.

2.3 System Limitations / Ramifications

During the development of the Fatigue Design Consultant, a number of assumptions were necessarily made. These assumptions, along with other constraints, such as those produced from incorporating FDC into the BFI system framework, resulted in a number of limitations within the system. It should be noted, however, that the prototype FDC system is a first step in the solution of the problem. FDC is intended to serve as a demonstration of the suitability and effectiveness of such a system in the domain, and cannot be considered, in its present form, a complete system without potential shortcomings. Therefore, these system limitations can help serve as guidance for future work to be conducted in the domain, and areas to be addressed in future system development.

The first limitation of FDC deals with the scope or focus of the system. This limitation resulted from the incorporation of FDC into the BFI system, and the scope of that system. As stated before, in order to simplify the development process and facilitate the incorporation into the BFI framework, the system was limited to deal only with the preliminary qualitative design of steel I-girder bridges, the same type of bridge targeted by BFI. While this type of structure does represent a large percentage of bridges designed for use in the U.S. highway system and is particularly susceptible to distortion-induced fatigue, there are other types of bridges (i.e. tied-arch bridges) that are also prone to fatigue damage which cannot currently be designed with the aid of FDC.

Another limitation of the system is that it focuses primarily on fatigue considerations and how they pertain to bridge design, and pays minimal attention to other factors that may affect the design of the structure. Included in these factors are fabrication and erection considerations, relative costs of alternatives, and aesthetics. In practice, these considerations play a significant role in the selection of bridge parameters and details. For example, a particular detail that is resistant to fatigue may be expensive or difficult to fabricate, and therefore avoided by the designer. The system's practical effectiveness could be improved if an FDC evaluation would take all of the factors mentioned above into account. While work is currently being conducted on the critique of beam-to-column connection designs from multiple viewpoints (i.e. designer, fabricator, and erector) [Barone 90], this multi-agent capability has not yet been incorporated in FDC.

Another limitation of FDC results from the nature of the problem being addressed. Fatigue cracks usually initiate from flaws at connection details, and since bridges, especially welded structures, cannot be fabricated without flaws and stress concentrations, fatigue problems will always exist. While good detailing can reduce their number and severity, "the need to connect members makes their complete avoidance impossible" [Chen 88]. Therefore, while use of the system should help minimize the problem, fatigue cracking will always be present. This fact emphasizes the importance of in-service maintenance and inspection of bridges, a primary focus of the Bridge Fatigue Investigator system.

Finally, the fact that the system concentrates solely on the preliminary qualitative design of a bridge, and does not possess the capability to aid in the quantitative phases of design, will limit the usefulness of FDC. The system will be applicable only in the qualitative portions of design, not the entire design process. In addition, any portions of the qualitative design that are influenced by quantitative parameters will have to be evaluated independently from the pertinent quantitative factors. This existence of incomplete knowledge will result in an imprecise evaluation, and may require the user to cycle through the design with FDC, as pertinent quantitative parameters are determined.

Two of the limitations mentioned above may tend to diminish the effectiveness of

FDC in a professional environment. First, the system's focus on fatigue considerations alone may produce an evaluation which is impractical in a professional environment. Second, the lack of quantitative capabilities in FDC and the resulting limitations may result in hesitation by the practicing professional to use the system. It is recognized that FDC will require a good deal of effort (enhancements and extensions to address these limitations) before the system is ready for effective use in a professional environment. The FDC prototype, however, should serve as a viable base upon which a system suitable for professional use can be built.

2.4 System Output

The commentary and recommendations presented to the user by FDC are dynamic, meaning they are generated according to the specific information for the particular bridge being evaluated, and are not predetermined. After each selection made by the user, the system evaluates the pertinent information within its knowledge base and determines the positive and negative aspects of the selection (possible ramifications that may be incurred), and recommends what it believes to be the best alternative based on what is known to that point in the design. This dynamic generation is importantant because it allows the faithful evaluation of specific, unique cases, whereas a statatic checklist may not be applicable to certain design scenarios. It is also important bececause different decisions made by the user can result in different ramifications and recommendations, thereby allowing the user to trace the viability and performance of alternative designs (to the extent of FDC's knowledge base).

It must be noted that the look-ahead capability of FDC is not considered intelligent.

This means that the system presents commentary on possible ramifications that may be incurred at a later stage in the design, and does not attempt to fill in the information it would need at that point to make a concrete prediction of what ramifications will occur. The same is true for the recommendations made by the system, which are based only on the information available at that point in the design. However, one important feature of the system is that the questions that the user are asked are dependent on the information that is already within the system's knowledge base, and therefore, like the commentary and recommendations, are also dynamic.

2.5 Summary Of System Overview

The FDC system operates as a stand-by advisor to the bridge designer as the preliminary, qualitative design of a steel I-girder bridge is generated, providing commentary and recommendations on the fatigue performance of design selections made by the user. The system provides commentary to the user on the influence of general bridge characteristics on the fatigue performance of individual details on the structure, and evaluates the topology and connectivity of each detail for fatigue performance.

FDC is intended to demonstrate the viability and suitability of a knowledge-based system in the domain. As a first step in addressing the task of producing fatigue-resistant bridge designs, the FDC prototype possesses a number of operating limitations. Included in these is an evaluation based solely on fatigue considerations, and the restriction of use of the system to the qualitative portions of the design process. The initial FDC prototype, however, serves as a test bed and potential platform for further system development.

3. Problem Formalization

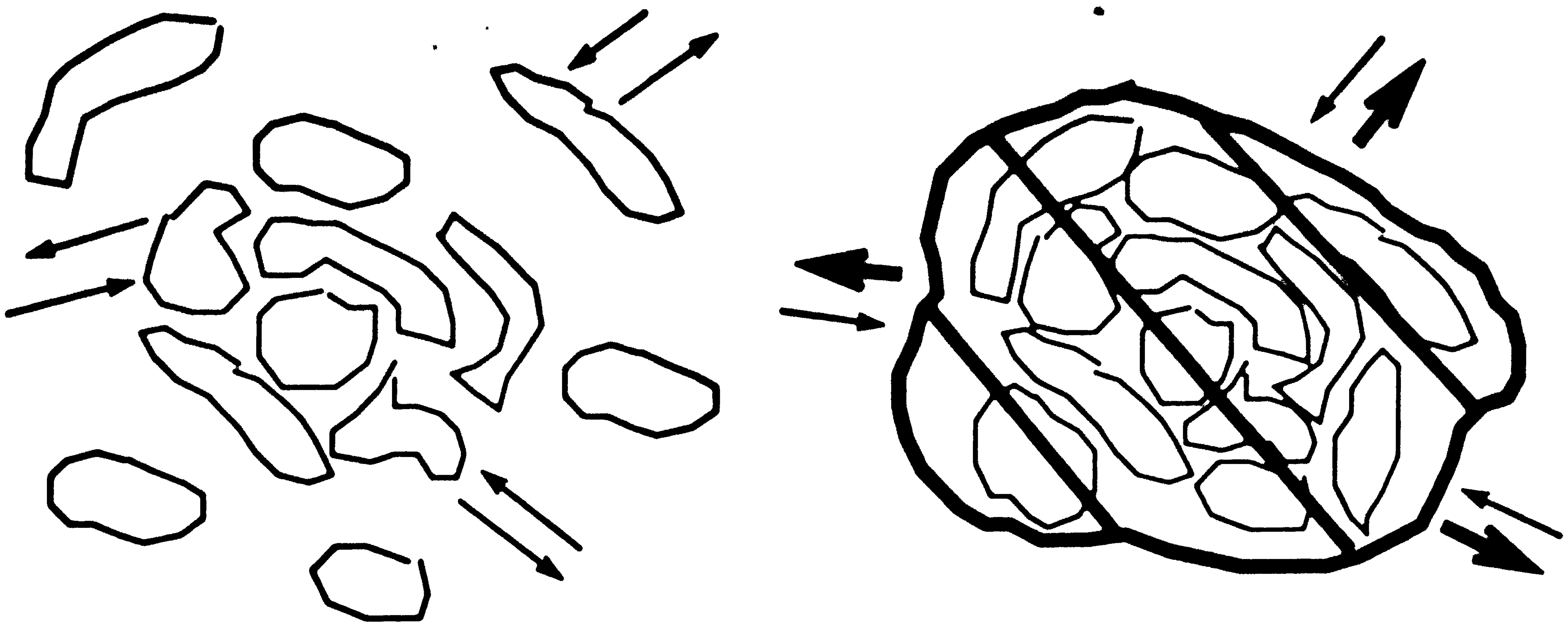
This chapter describes the preliminary development work that was necessary to formalize both the problem to be addressed by FDC and the knowledge utilized to help solve the problem. This development work included the acquisition of knowledge required in the domain, and the organization and formalization of this knowledge into a coherent, rational framework. Included is a discussion of the strategy utilized to establish a bridge design process to be modeled in FDC, and the manner in which the domain knowledge was molded into a more representative body of knowledge which takes into account the interaction of different bridge details.

3.1 Knowledge Acquisition And Formalization

The knowledge acquisition process was on-going throughout the year-long development of FDC. The primary source of knowledge was an expert in the field of fatigue and fracture of steel bridges. The acquisition of knowledge from this source was accomplished in a number of ways. Personal knowledge acquisition sessions were utilized at the initial stages of development to help determine the general scope and direction of FDC. In addition, these sessions were conducted throughout the development of FDC to clarify specific problems or answer questions on varied aspects of the influence of fatigue on bridge design. Much of the knowledge utilized in FDC was gleaned from the reports, documents, and files of the domain expert [Fisher 77, Fisher 84, Fisher 89, Demers and Fisher 89, Fisher et. al. 89] and reviewed at the personal knowledge acquisition sessions [Fisher 90]. Other sources of knowledge included the various bridge design codes [AASHTO 89] and other published work on fatigue and fracture [Barsom and Rolfe 87], as well as the occasional input of other experts within the domain [Yen 90, Becker 90].

The most difficult task in the development of FDC dealt not with the direct acquisition of the domain knowledge, but with the formalization of the knowledge into a rational, representative body of knowledge. This problem resulted from the nature of the knowledge itself. Much of the expert knowledge was in the form of detached "facts" or experience-based heuristics that addressed only isolated parameters or details, and which was often empirical in nature. While this knowledge could adequately be expressed in the form of general rules and applied in what is known as a first-generation knowledge-based system (a KBS that relies purely on heuristic knowledge in the form of rules), the development of a second-generation knowledge-based system (a KBS which posses a deeper model of reasoning beyond pure heuristics) could not be accomplished without the formalization of the knowledge into a comprehensible body [Kowalik 86]. The methodology by which the disjoint knowledge was formed into a body of knowledge is described below.

A primary goal in the development of FDC became the transition from the empirical reasoning characteristic of the knowledge itself, to a more causal reasoning that could effectively express the knowledge of the expert within the context of a rational framework, an organizational model which takes into account the interaction of different pieces of knowledge. A representation of both empirical reasoning and causal reasoning is depicted in Figure 3.1 on page 26. In this figure, empirical reasoning is characterized as a collection of disjoint, detached collection of facts or rules that operate alone, while causal reasoning is characterized as a collection of facts, rules, and principles bound in a framework, forming a more comprehensive body of knowledge that



Empirical Reasoning **Causal Reasoning**

Figure 3.1
Different KBS Reasoning Schemes

operates as one. The reasons for developing this type of causal system, and its superiority to the purely heuristic-based type of system is emphasized by [Kowalik 86].

The need to organize the knowledge acquired into a rational model or framework was strongly felt during the adoption of a bridge design process to model in FDC. It was here that the interaction of individual parameters and details of a bridge design would have to be represented in a deeper model. This model manifested itself in the form of a network of Design Dependencies (relationships between parameters and details). This Design Dependency network reflects the interaction of individual parameters in the design process as well as the relation of these individual parameters to the overall fatigue-performance of the structure. By constructing this model, FDC's design evaluation would not be performed as simply a heuristic check of isolated details, but would rather take their interaction into account. A detailed description of the Design Dependency network can be found in Section 3.3.

3.2 Bridge Design Methodology

Some of the most important decisions in the development of the FDC system were made in selecting a bridge design process to follow. This process is reflected in the general stages FDC steps through with the designer as a qualitative bridge design is generated. The first step in determining the design process to model was isolating the portion of the bridge design procedure that would be focused on. In practice, the bridge design procedure tends to flow from the conceptual phase (the **selection of general bridge parameters**, which are the characteristics that can generally be used to describe the bridge), to the **preliminary quantitative design**, to the **detailed design**, as shown in Figure 3.2. This procedure, however, involves quantitative decisions in the preliminary phase, and often handles the detail design as something of an

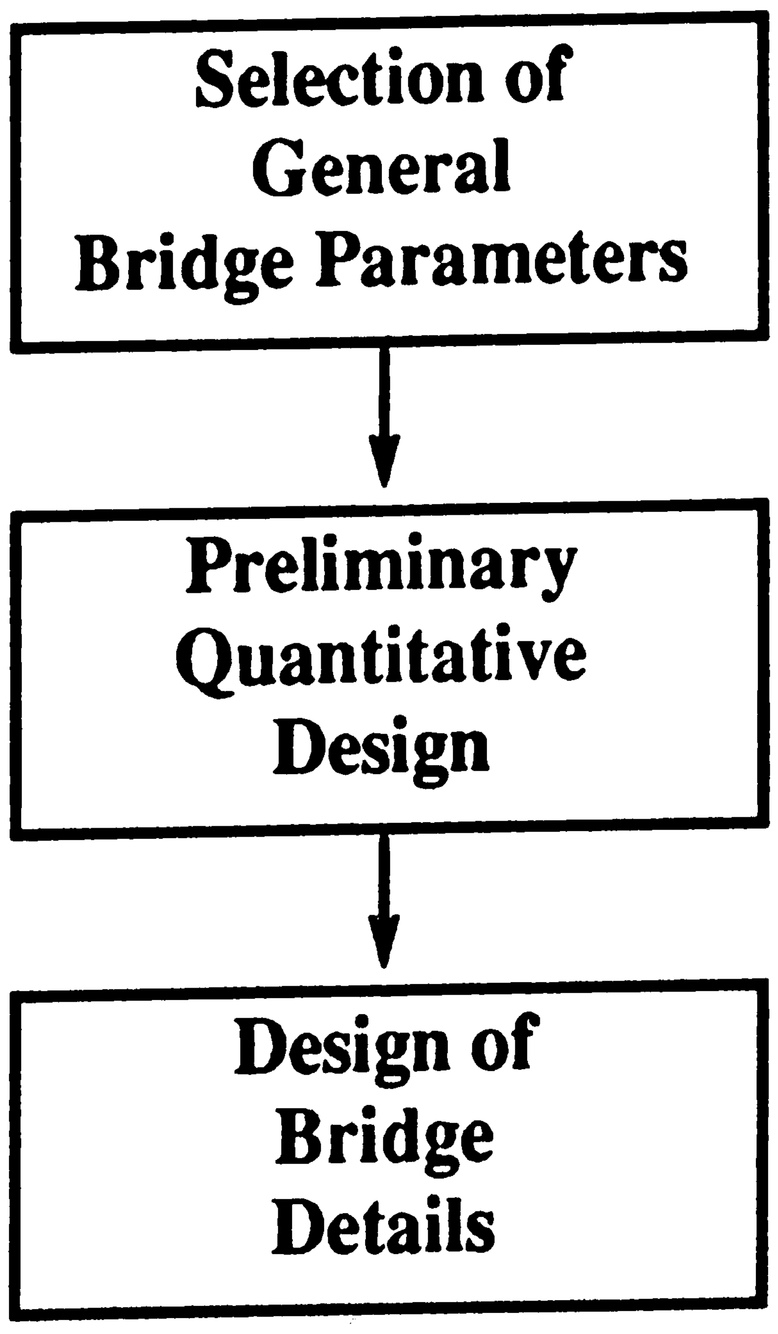


Figure 3.2
Accepted Bridge Design Process

afterthought. As stated in Section 2.1, it was desirable to avoid the quantitative portions of design and the broad extensions to the BFI core they would mandate, and focus on the qualitative design of details to be used on the bridge.

It was therefore determined that, for FDC, it would be best to modify this procedure to flow from the conceptual phase, to the conceptual (qualitative) design of details, and then to the quantitative portions of design, as shown in Figure 3.3. The design process adopted FDC would operate in the conceptual phases of the design procedure in this new scheme. This would place a greater emphasis on the design factors which most greatly affect the structure's fatigue performance [Fisher 90]. It should be noted that portions of the conceptual detail design are dependent on parameters determined in the quantitative design. Therefore, at portions of the conceptual

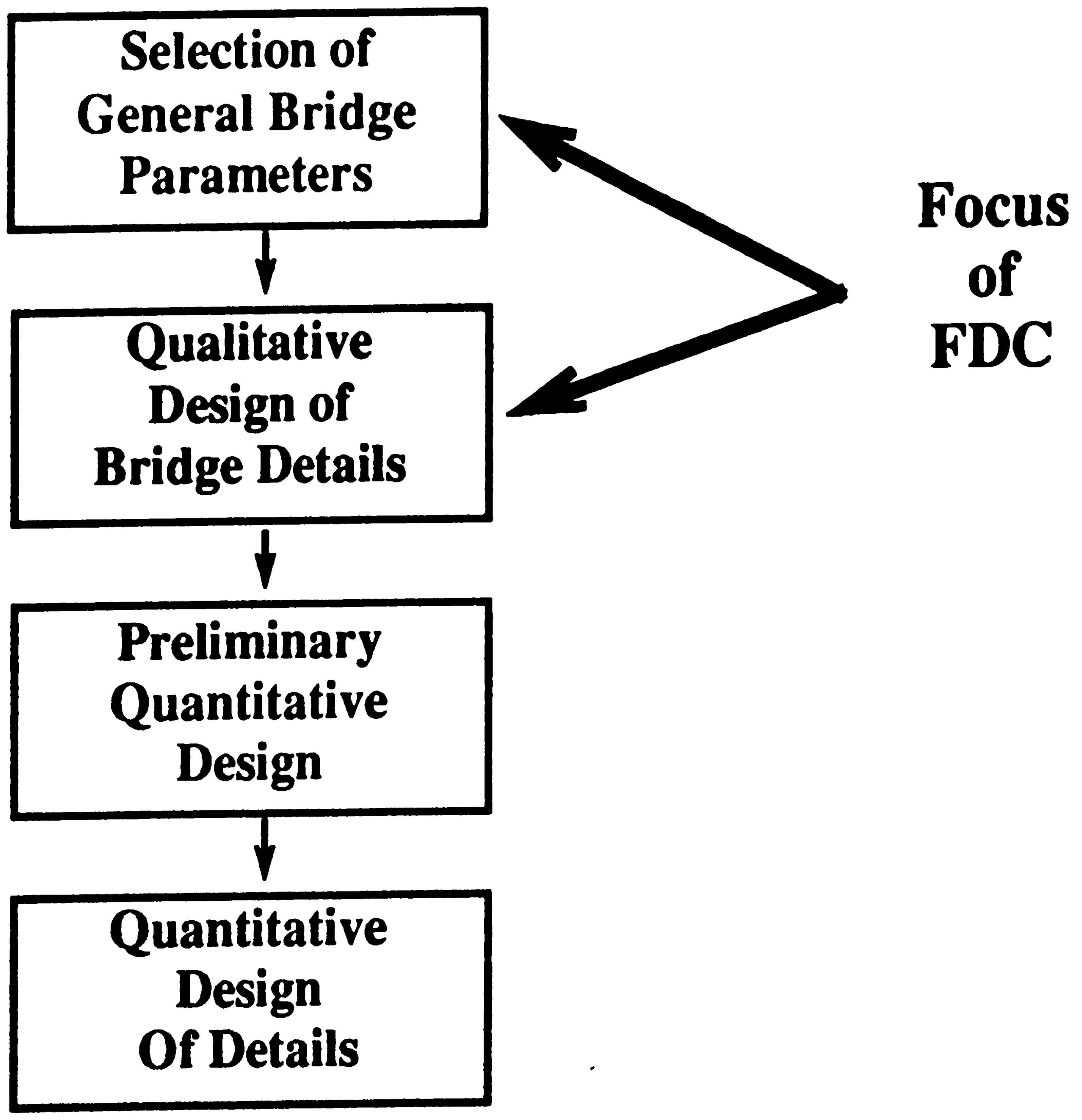


Figure 3.3
Bridge Design Process As Modified For FDC

detail design in FDC, there is not enough information for the system to make a precise evaluation or recommendation. An example of this occurs in the determination of whether or not a bottom lateral bracing system is necessary for a particular bridge, and the configuration this system should assume. This conceptual detail design is dependent on the size of the main girders and the diaphragm spacing, and therefore the designer will have to assume a bottom lateral configuration until the necessary calculations can be performed. However, this is not unlike the conventional design process which is often cyclic, calling for assumptions and modifications to be made, in an iterative sequence, by the designer.

Since FDC was to operate in the conceptual phases of the design process, it was necessary to identify and define the parameters which made up each of these phases. In conjunction, it was necessary to determine the factors within these phases that would influence the fatigue performance of the structure. These parameters and factors were studied through research conducted in the domain during the knowledge acquisition stages of the development of FDC. Most critical to the development of a rational model within the domain was the determination of how these individual factors would interact to affect the structure's fatigue characteristics.

It was found that the general bridge parameters selected by the designer in the conceptual phase of the design process were influenced by numerous non-structural factors [Becker 90]. For example, deciding whether to make the bridge a simply-supported or continuous structure (a parameter which affects the structure's fatigue performance) was influenced by the geotechnical characteristics of the bridge site. Therefore, these geotechnical characteristics indirectly affected the structure's fatigue performance. It was therefore necessary to both determine how far upstream in the conceptual design FDC would operate, and whether or not the system would provide commentary and recommendations on the type of non-structural factors which affected the selection of the general bridge parameters. A list of some of these non-structural factors is provided in Table 3.1.

It was decided that the non-structural parameters that did not directly affect the fatigue performance of the bridge would not be addressed. It would be left up to the designer to study these factors himself, and select the general bridge parameter that, in turn, would have direct influence on the fatigue performance of the structure. This is not to say that all of the general bridge parameters are structural characteristics. It

Table 3.1
Non-Structural Factors Which Influence General Bridge Parameters

- Site Conditions
- Foundation Considerations
- Erection Consideration
- Environmental Impact
- Location
- Cost
- Aesthetics
- Fabrication Considerations
- Traffic Conditions
- Design Specifications and Codes

was determined that a number of non-structural factors did have a direct fatigue influence and would therefore be considered a general bridge parameter within FDC (i.e. the projected average daily truck traffic (ADTT) that the bridge is to be subjected to, and the design life of the structure).

While the isolation of the particular bridge details which were susceptible to fatigue problems was fairly straightforward, establishing a methodology for their design with an emphasis on fatigue considerations was quite difficult. There is no precise format or established procedure for the integrated design of these details. While a design procedure and rules governing the fatigue-susceptibility of each individual detail existed, their interaction was not addressed. This presented a problem, because the interaction between different details often greatly affects the fatigue performance of the structure. It was therefore necessary to define a methodology which took into account the interaction of the individual details on a structure and which could be formalized into a procedure that could be followed in FDC. The first priority became establishing the interaction of each of the different details and parameters, in a network of Design Dependencies (relationships). The next step would be formalizing these Design Dependencies into a hierarchy that would be the basis for the design methodology and which would form the backbone of the model-based (causal) representation of knowledge within FDC.

3.3 Design Dependencies

Towards the goals of a more causal-based body of knowledge, and the development of a rational methodology for the design of bridge details, the relationships between different details, and how they affected the fatigue performance of the structure, were studied. These relationships were systematically researched, reviewed, and modified during the knowledge acquisition phase of the development of FDC. These relationships were labelled Design Dependencies by the author. This name reflects the fact that the design of one specific detail may be dependent on the design of other details on the bridge.

The bridge details determined to be critical to the fatigue performance of the structure (determined from problems that were discovered to exist in in-service bridges), were to be addressed by FDC. During the formalization of the relationships between these details, it was discovered that some bridge details tended to affect the fatigue performance of a great many other details, while still others seemed to have little influence. This fact suggested that the details upon which the design of a great many other details were dependent, were most critical. It was postulated by the author and corroborated by the domain expert, that by properly designing these critical details for fatigue effects first, the design of the details that were dependent on them could also be improved. This would result from a lookahead during the design of the critical details. By presenting the designer with the type of ramifications that could occur during the design of details that would follow, and by suggesting a recommended alternative, the system could influence him to make the best possible design selections. The recommended alternative would be the one which would not only provide for the most fatigue-resistant design of the current detail being generated, but also those details to be designed later that were dependent on the current detail.

The order of details that have the greatest to the least influence on other details is given in Table 3.2 on page 33. By organizing the Design Dependencies for the details

Table 3.2
Design Detail Influence

Greatest Influence
On Other Details

↓

Least Influence
On Other Details

- Main Girder Configuration
- Lateral Bracing System
- Stiffener Configuration
- Floorbeam Configuration
- Diaphragm System
- Stringer Configuration
- Stringer Diaphragm System

in a hierarchy based on this relative influence, an order of detail design for FDC was developed. The design would start with the most critical detail (the detail that had the greatest influence on other details) and proceed down to the detail with the least influence. The resulting network of Design Dependencies resembles a lower-triangular matrix with the individual details on the diagonal (most critical detail in the upper left corner, least critical detail in the lower right corner), as shown in Figure 3.4 on page 34. The influence a particular detail has on a less-critical detail can be found in the network, in the column below the particular detail in the row of the less critical detail of interest. For example, if the influence of the **Main Girder Configuration** (design of this detail) on the **Floorbeam Configuration** is desired, it can be found in the column below **Main Girder Configuration** in the row of **Floorbeam Configuration** (shaded in Figure 3.4 and listed in Appendix B, FDC Design Dependencies, on page 93). A listing of the Design Dependencies is provided in Appendix B.

While the possibility existed that a certain detail farther down on the list of critical details could influence a detail higher on the list, it conveniently worked out that this case was a rarity. In addition, when this case did exist, the influence of the more critical detail on the less critical detail usually was of much greater importance to the overall fatigue performance of the structure. Therefore, it was determined that the top-down approach to the design of details (from most critical to least critical) was adequate for this pilot-prototype system.

The formulation of the Design Dependencies helped organize the knowledge and rules for design into a much more comprehensive body of knowledge, which reflected the interaction of different details. In addition, by organizing these Design Dependencies into a hierarchy, a bridge design process was adopted for implementation in FDC.

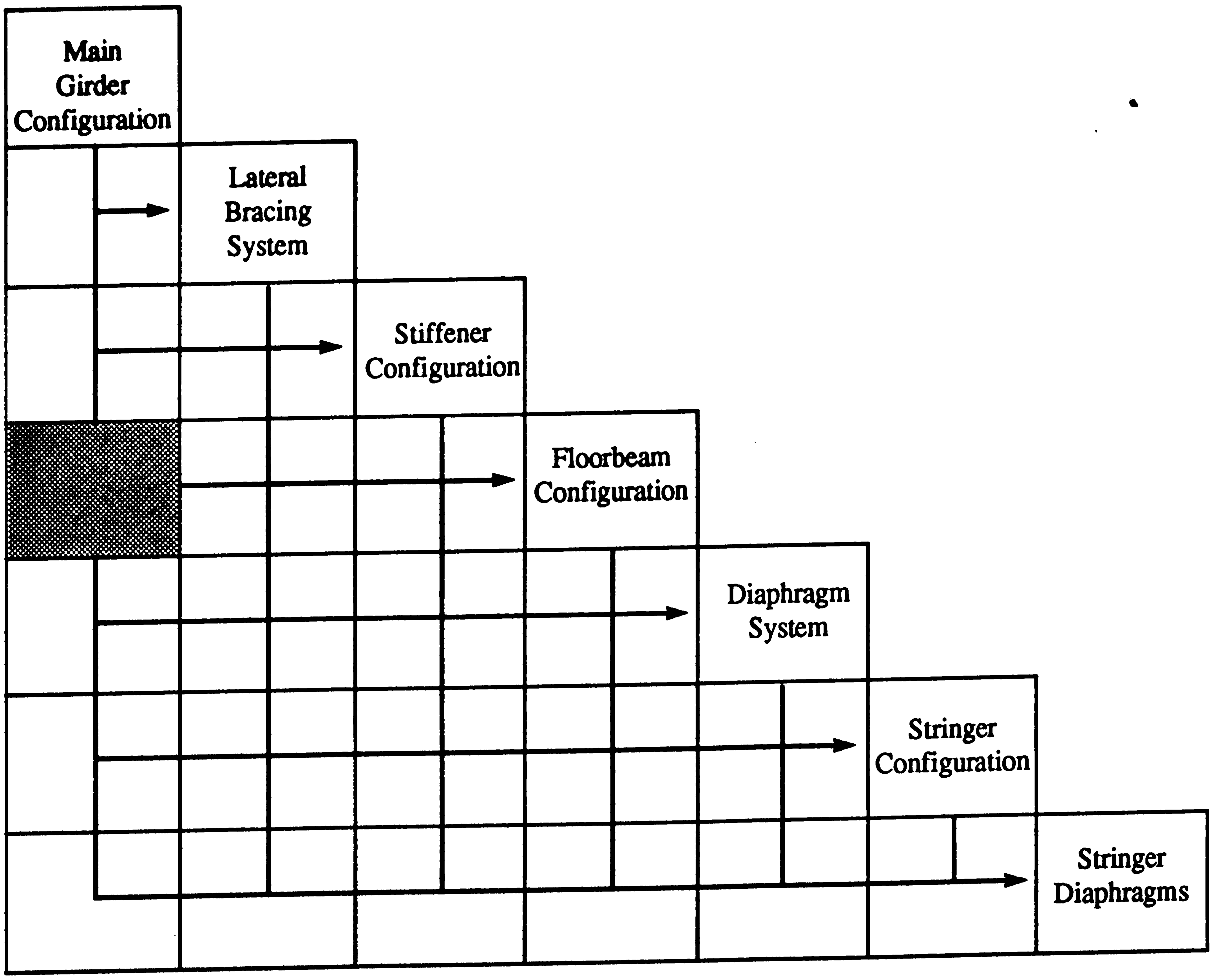


Figure 3.4
Representation Of FDC Network Of Design Dependencies

3.4 Summary Of Problem Formalization

The process of formalizing the problem addressed in FDC began with the acquisition of knowledge within the domain, a process that was on-going throughout the system's development. Much of the knowledge was in the form of disjoint facts which dealt with isolated parameters or details. The need for a more systematic model of reasoning led to the development and organization of a network of Design Dependencies which resulted in a more representative body of knowledge, which expressed the interaction of the different parameters and details modeled within the system.

4. Implementation

This chapter provides an overview of the structure of the Bridge Fatigue Investigator (BFI) system. Section 4.1 will examine the framework or architecture of BFI. This framework serves as a means of categorizing and organizing the knowledge in the system. Sections 4.2 and 4.3 describe the scheme used to represent the knowledge within the knowledge framework. The existing framework and representation of knowledge in BFI is important because it served as a model for, and often dictated aspects of, the computer implementation of the FDC system, which is linked to it, and which is discussed in Section 4.4. Finally, Section 4.5 provides a brief description of the Knowledge Base Editor (KBE), a means of modifying and extending a knowledge-based system, which is utilized as a system utility for FDC.

4.1 Open-System Framework For BFI

The basic concepts of the open-system framework were mentioned in Section 1.4.2. At this point, however, it is necessary to discuss this framework, and how it is implemented in BFI, in greater detail. The key concept of the open-system approach, "is to partition knowledge into a kernel (primary, domain-specific knowledge) and a scenario (targeted application-tasks knowledge) level. A layer of utilities is implemented to provide interaction between the two knowledge bases and to support inferences and operations of the model" [Wong and Wilson 89]. Figure 1.2 on page 10 provides a view of the general open-system framework.

This framework addresses the fact that many tasks within a particular domain share common knowledge requirements and also have different, application-specific needs. Within the open-system framework, the application-specific knowledge for each task is placed in a separate module or scenario, and the commonly required knowledge is concentrated in a core, and made accessible to each scenario module through system utilities. Organizing a knowledge-based system in this fashion provides a flexible architecture which is suited to the following [Wong and Wilson 89]:

- Knowledge organization which permits formal rapid prototyping.
- Organized knowledge expansion and modification.
- The use of knowledge for multiple purposes.

Within this framework, each scenario can communicate with the core knowledge as well as external knowledge sources (i.e. application-specific databases). This framework also provides for the communication and sharing of knowledge between different scenario modules through the central core. Without the open-system framework, the commonly required knowledge would have to be included in each application-specific scenario, and there would be a combinatorial explosion of knowledge translation and mapping among various knowledge modules for scenario communication [Wong and Wilson 89].

Within BFI, the application-specific tasks of providing the user with inspection advice and an evaluation of existing fatigue damage were separated into different scenario modules (Pre-inspection and Post-Inspection, respectively). Both of these scenarios share the need for knowledge on the structural topology and connectivity of a bridge being evaluated, knowledge which is resident within the core. It was determined that the task of evaluating a proposed bridge design for fatigue performance also shared the need for this core knowledge. It therefore became apparent that a prototype FDC system could be implemented as a scenario module with knowledge pertaining to the fatigue performance of proposed bridge designs linked to the existing BFI knowledge core. Figure 4.1 shows the framework of the existing BFI system, extended to include the FDC scenario module. This figure depicts FDC as a scenario module (along with pre and post-inspection) operating with the central BFI knowledge core. A

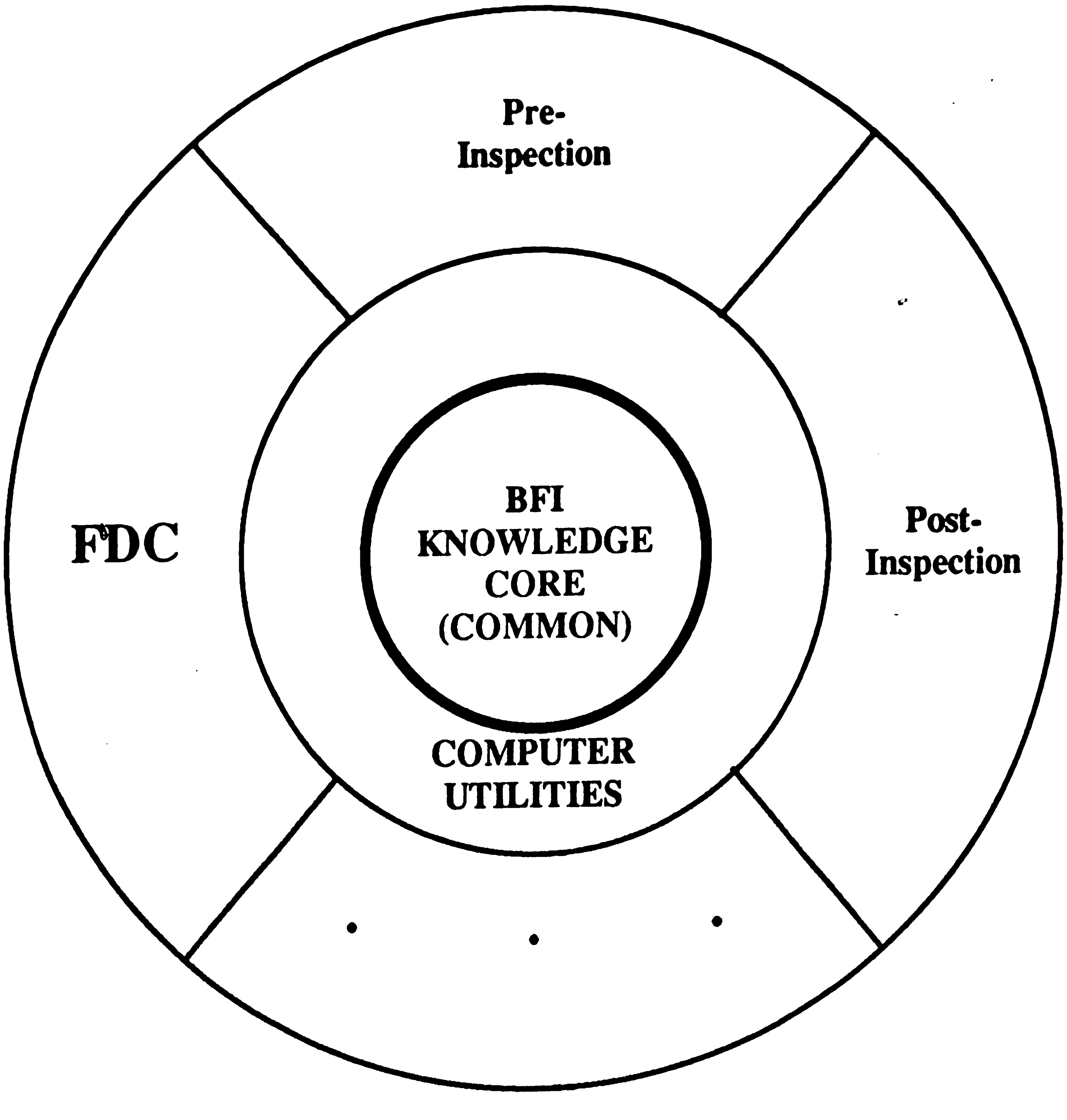


Figure 4.1
Open-System Model Applied To BFI

more detailed description of the open-system model can be found in [Wong and Wilson 89, Wong and Wilson 88].

4.2 Object-Oriented Knowledge Representation

The previous section described the open-system architecture adopted for use in BFI, and how the knowledge within the system is partitioned into a core module and separate scenario modules. "The actual implementation of those modules is done largely using an object-oriented knowledge representation" [Chen 88]. The selection of an object-oriented knowledge representation scheme allows reduced system development time, and enhanced modularity, reusability, efficiency, and modifiability of the system [Chen, G. 90]. The object-oriented approach, and its influence on these factors is described below.

An object-oriented representation scheme is based on the fundamental principle which calls for, "the packaging of both data and procedures into structures related by some form of inheritance mechanism" [Jackson 86]. Basically, the knowledge engineer defines, "individual **objects**, which represent the entities which the system is to reason about, and **methods**, which describe the inference rules and attributes associated with those entities" [Chen 88]. Within this scheme, inferencing can be accomplished through the sending of messages to specific objects which then utilize their appropriate methods to achieve a result.

[Wong and Wilson 89] describes an object as a private memory consisting of private data, and methods that can access that data. Interacting with other objects in the

KBS through an interface, an object can accept messages that call upon it to access, modify, or return a portion of its private memory. Messages tell a particular object what needs to be done, and the object chooses the appropriate method from a list of things it knows how to do [Cox 86].

[Chen 88] defines the fundamental constituents of the object-oriented approach as follows:

An **object** consists of some private data and a collection of procedures that can access that data. An object encapsulates both data and procedures that operate on that data, thus combining in one entity both state and behavior. The procedures are called **methods**. There are two types of objects; an object can be either a **class** or an **instance** of a class. These are defined below.

A **method** is a name for a procedure associated with, and localized within an object. A method is accessed and executed when a **message** matching the method name is sent to the object containing the method.

A **message** is a request directed to an object to carry out one of its operations (methods). A message "tells an object what it should do", letting the object determine how to do it. Messages are typically invoked by the methods of other objects.

A **class** is a description of a group of similar objects. A class is an object which describes the implementation of a set of similar objects.

An **instance** is one of the specific objects within a class. An instance inherits the general characteristics of its class and locally defines additional ones specific to itself.

These constituents and their operating schemes are demonstrated in the following example, which is characteristic of the knowledge representation in BFI and FDC. Figure 4.2 depicts an example of the object-oriented approach.

A specific class of objects is physical objects. Two instances of this class are members and binary connections, which are classes of objects themselves. Instances of these classes are girder and girder web to girder flange (gwtgf) connection, respectively. The object girder contains the method girder-type, which prompts the user for the type of main girder used on the bridge (rolled sections or built-up sections), and, depending on the this parameter's value, performs an associated procedure. If the parameter value is built-up girders, then the girder object will send a message to the gwtgf connection object requesting this object to return the type of connection used.

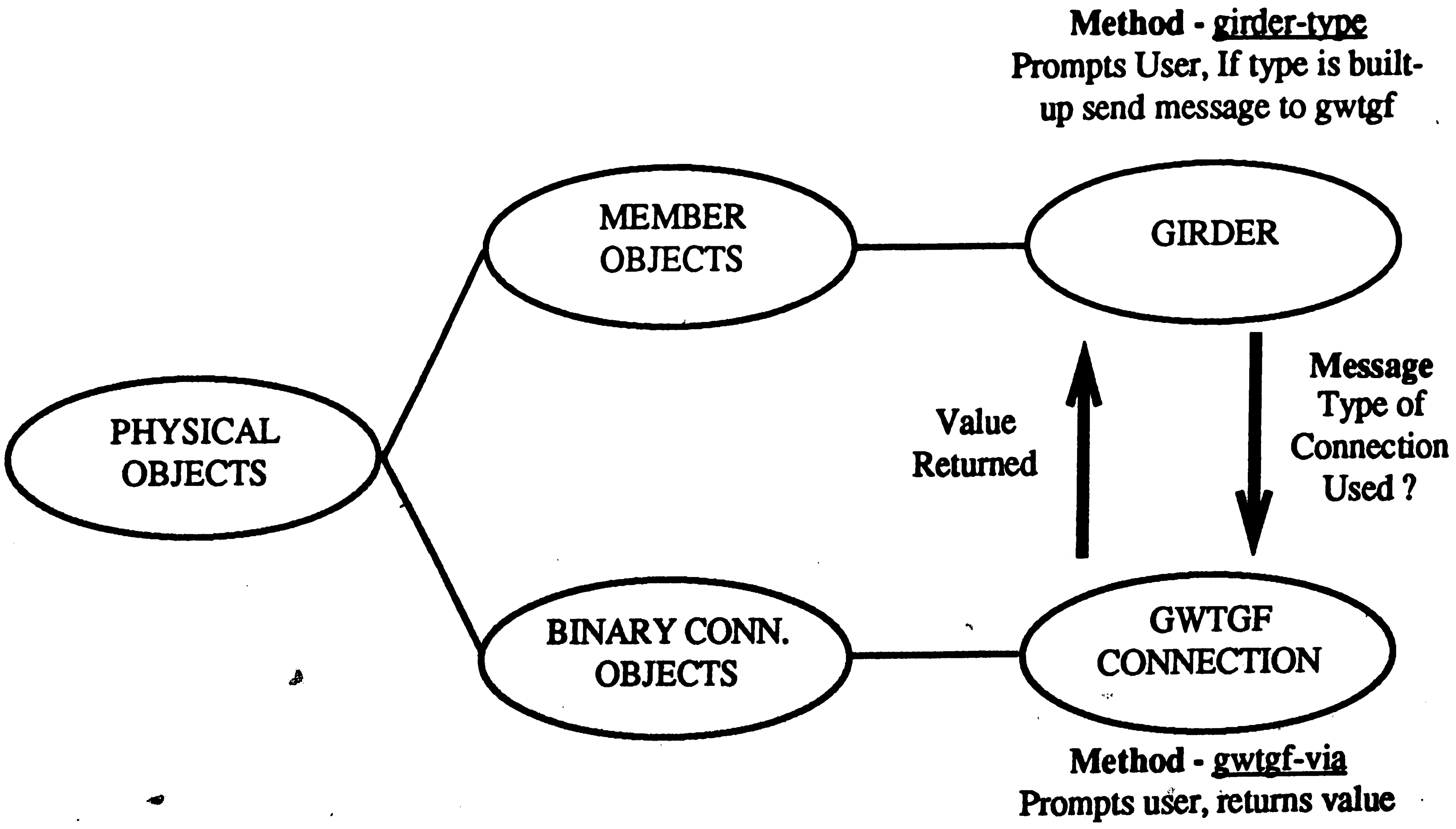


Figure 4.2 Example Of Object-Oriented Operation

The gwtgf connection object will then use one of its methods (gwtgf-via) to prompt the user for the type of connection used (continuous fillet weld, intermittent fillet weld, groove weld, or a bolted / riveted connection). The appropriate value will then be returned to the girder object. This value is then stored in the knowledge base for future reference.

By utilizing object-orientation, the physical topology and connectivity of a bridge and its components and connections, along with abstract entities in the domain (i.e. those necessary to perform application-specific tasks, such as the assessment of existing cracking in a particular bridge for BFI, and the generation of commentary and recommendations for specific bridge details for FDC) are represented in BFI and FDC.

4.3 Hybrid Knowledge Model

It was determined during the implementation of BFI that the object-oriented knowledge representation scheme would not be sufficient to model the entire complement of domain knowledge. “It is no surprise that no single paradigm adequately handles the diverse kinds of problem-solving that humans routinely perform” [Chen 88]. Object-orientation was utilized to represent the descriptions and inferences of physical and abstract entities. However, global “overseer” routines, those which guide the general flow of operation of the system, the system’s user-interface, and explanation facilities would be best represented in a logic programming scheme [Chen 88]. Logic programming provides declarative semantics and a tight resolution mechanism which, when coupled with an object-oriented data structure, produces a hybrid scheme which, “allows powerful reasoning strategies with sufficient computing efficiency for prototype development" [Wong and Wilson 89]. The hybrid BFI system was implemented using the Prolog computer language. "Prolog's rule-based processing capability fits neatly with the object-oriented approach" [Stabler 86], and is well-suited to logic programming.

4.4 Integration Of FDC Into The BFI Framework

4.4.1 Organization Of FDC Knowledge

After the knowledge acquisition and formalization stages of the development of FDC, it was necessary to organize the knowledge into a knowledge representation scheme which could be integrated into the BFI framework. The first step in this process was to separate the FDC knowledge, based on where individual portions of the knowledge should be placed in the system framework, either to be added to the BFI core, placed in the FDC scenario module, or incorporated into the user-interface supporting mechanisms. The following organizational methodology was adopted:

A preliminary step was to determine if the specific piece of knowledge related to either:

- The structural topology or connectivity of the bridge.
- The user-interface supporting mechanisms.
- The specific task of bridge design.

First, If the knowledge related to the structural topology and connectivity, it was necessary to determine if it was generic (suitable for multiple applications within the domain) or specifically related (application-specific) to the task of bridge design. If the knowledge was generic, then it was to be placed in the BFI core. If the knowledge was specifically related to the task of bridge design, then it was to be placed in the FDC scenario module.

Second, if the knowledge related to the user-interface support mechanism, it was necessary to determine if the function could have been carried out by the BFI user-interface modules. If the function could have been performed by the BFI module, then the BFI mechanism was utilized. If the function could not have been carried out by an existing mechanism, then modifications or additions to the user-interface module were necessarily made.

Third, if the knowledge was specifically related to the task of bridge design, then it was placed in the appropriate location of the FDC scenario module.

After the task of organizing the knowledge was carried out, the appropriate modifications to BFI, and the development of the FDC scenario module could be addressed, as described in Sections 4.4.3 and 4.4.4, respectively.

4.4.2 Objectization of FDC Knowledge

It was decided that object-orientation would be utilized wherever possible as the representation scheme for the FDC knowledge. This decision resulted from the positive characteristics of object-orientation, and the fact that FDC could be more easily integrated into the BFI framework if a consistent knowledge representation scheme was utilized. The object-orientation of the FDC knowledge resulted in a list of questions which should be answered to facilitate the objectization of any domain:

a) What specifically needs to be modeled ?

For example, in BFI and FDC, it was necessary to model the physical topology and connectivity of steel I-girder bridges. In addition, the knowledge on fatigue and fracture needed for BFI Pre and Post-Inspection and FDC had to be modeled.

b) What level of abstraction should the model be taken to ; or possibly different levels for different applications ?

For example, in BFI Pre and Post-Inspection applications, it was necessary to represent the different plate elements which comprise the components of the structure (i.e. so that the direction of stress and how it relates to the propagation of cracking on the bridge could be reasoned about). It was, however, only necessary to model the components themselves for FDC applications (i.e. not necessarily the plate elements that comprise the components).

c) What characteristics of the model are global ?

For example, in the BFI / FDC system, the physical topology and connectivity of the structure are global (i.e. it relates to all applications within the domain).

d) What individual components or entities comprise the model for the level of abstraction desired ?

For example, in BFI Pre and Post-Inspection, possible physical components include girder web and flange plates, floorbeam web and flange plates, attachment plates, etc. For the FDC level of abstraction, components include girders, floorbeams, lateral gusset plates, etc.

e) What are the important characteristics of the individual components and / or their functions ?

For example, important characteristics of a main girder include whether the section is rolled or built-up, whether or not cover plates are used, and the type of stiffeners used (if any).

f) How are these individual components related ?

- Physically (i.e. spatially, connectively, load paths)

For example, what the level of the floorbeams is with respect to the main girders.

- Abstractly (i.e. mutual exlusivity, existence dependency)

For example, in BFI / FDC, if there are more than four main girders, it is assumed that there will be no floorbeam / stringer system. Also, if there is a lateral connection plate, there must be some type of connection between this plate and the main girder.

- **Functionally (i.e. performance influence)**

For example, if a transverse attachment plate intersects a lateral gusset plate, the fatigue performance of the lateral gusset may be worsened.

g) What can be inferred about a particular component / entity depending on the characteristics of other components / entities ?

For example, if a main girder is a built-up section, it can be inferred that there are no cover plates used.

h) Will the model ever be extended to other applications, or to include additional components / entities ?

For example, if the BFI / FDC system were to be extended to another type of bridge (i.e. box-girder bridges), additional components needed to describe the structure, such as box-girder sections and internal diaphragms, would have to be incorporated into the system.

By formalizing the answers to these questions, the objectization of a domain can be simplified. After these questions were answered for FDC, the objectization process was all but accomplished. At that point, a check of the consistency between the FDC objectization and that utilized in BFI was performed.

4.4.3 Modification Of BFI Core Knowledge

After the organization and objectization of the FDC knowledge, the knowledge relating to general bridge topology and connectivity (and therefore appropriate for placement in the BFI core) was compared to the objectized knowledge which was already within the BFI core. It was found that, while the level of abstraction was different (BFI possessed a finer level of abstraction of the bridge components, i.e. down to the level of individual plates in members), the FDC knowledge could be massaged into consistency with the knowledge already within the BFI core. There were only a few methods which needed to be added to the BFI core objects for FDC applications. For example, methods which described the design life of the structure and the action (composite vs. non-composite) of the girder and slab were added. This fact provided positive reassurance that the open-system model was effective.

4.4.4 Development Of FDC Scenario Module

The knowledge incorporated in the FDC scenario module was in essence an objectized representation of the FDC Design Dependency Network, and the heuristic rule-based knowledge acquired from the domain expert. The knowledge was separated into two general classes of abstract objects, Comment Objects and Recommendation Objects. An example of a Comment Object would be the object **object_comment_lateral_used**, whose methods determine the appropriate positive and negative aspects of the designer's choice of type of lateral bracing system (if any). An example of a Recommendation Object would be the object **object_recommendation_lateral_used**, which, based on the user's selection will make an appropriate recommendation, or suggest a more fatigue-resistant alternative. The methods within these objects produce commentary and recommendations by sending messages to the appropriate objects in the BFI core, and depending on the replies, perform the appropriate evaluation.

The module operates in the following fashion: as a design selection is made by the user, and this parameter instantiated, a message is sent to the Comment and Recommendation Objects to make an evaluation. The appropriate methods within these objects then obtain any needed information through message-sending, and trigger the appropriate evaluation which is presented to the user.

4.5 The Knowledge Base Editor

The Knowledge Base Editor (KBE) is a tool, developed independently from BFI and FDC, intended to aid in the development, modification, and / or extension of knowledge-based systems. The KBE provides a mechanism for the user, who may not be intimately familiar with either the knowledge representation scheme or computer programming, to specify the object content and structure in the knowledge core, and thereby build, modify, or extend the system. Basically, the KBE allows the user to express the relationships between and functions of different objects in a high-level representation language (between computer code and the written language), which is then transformed into the appropriate computer code and checked for inconsistencies by the KBE [Wong and Wilson 88].

A portion of the KBE is called the Pictorial Display Module (PDM). This module allows the user to see a graphical representation of the knowledge or query structure in a knowledge-based system. By being given this option, the user can more easily trace the problem-solving process taken by the knowledge-based system. This is of importance to FDC, because it allows the user to see alternative paths that can be taken through the design process and options that are available if different design selections are made. A more detailed discussion of the KBE and PDM are provided in [Chen G. 90, Wong and Wilson 88].

4.6 Summary Of Implementation

The FDC system's incorporation into the BFI system was facilitated by using an open-system framework in BFI. This framework provided for the partitioning of knowledge into a common knowledge core and application-specific scenario modules, such as FDC. It was found that the existing BFI knowledge core required only minimal changes to operate in conjunction with FDC. In addition, the object-oriented knowledge representation scheme utilized in BFI served as a model for the knowledge representation in FDC, which provided for ease of communication between the FDC scenario module and the BFI knowledge core. The organization and objectization of the FDC knowledge also led to the formalization of a general methodology for the development and implementation of knowledge-based systems, and the types of questions which should be answered during this process.

5. Validation Studies

5.1 Introduction

This chapter describes the validation studies performed to test the functionality and effectiveness of the FDC system. While there is no consensus about how to evaluate knowledge-based systems [Jackson 86], answering the following questions may help reveal potential strengths and weaknesses of the system [Chen 88]:

"Correctness"

- Is the system coming up with the right answers, and is it doing so for the right reasons ?

"Consistency"

- Is the modeled knowledge consistent with the expert's? If not, why not ?

"Performance"

- Is the knowledge representation scheme adequate or does it need to be extended or modified ?

However, the answers to these questions are subjective, depending on the definitions accepted for "adequate", "right", and "consistent". Therefore, it is necessary to define a standard by which the correctness, consistency, and performance of a knowledge-based system can be judged. This standard is discussed in Section 5.2. Section 5.3 describes the type of test cases utilized, and Sections 5.4 and 5.5 provide a description of two specific field studies and the results that were obtained by using the FDC system.

5.2 The "Gold Standard"

"In conventional analytical or experimental structural engineering research there is often a clear 'gold standard': an unequivocally 'right' answer" [Chen 88]. This standard is usually based on established principles or empirical data. However, since knowledge-based systems are generally developed for use in domains where decisions are highly judgemental, determining whether a system is performing appropriately or effectively (developing a "gold standard" for KBS evaluation) is difficult [Buchanan and Shortliffe 84]. If a gold standard could be developed, then comparison of the KBS's advice to this standard could provide a basis for system evaluation. Two potential "gold standards" exist [Buchanan and Shortliffe 84]:

1. What eventually turns out to be the "correct" answer for a problem, and
2. What a human expert says is the correct answer when presented with the same information as is made available to the expert system.

For the evaluation of FDC, the system's advice was compared to both of these standards. This provided both a check of the performance of the FDC system, and the system's consistency with the opinion of the domain expert. In addition, it was possible to perform a cursory evaluation of the domain expert's performance, by comparing the two "gold standards" to each other.

5.3 Types Of Test Cases Utilized

It was determined that, for FDC, the most viable way to compare the FDC advice to the established standards would be to use the designs of in-service structures, as opposed to proposed designs, as test cases for the system. By doing so, at least two of the questions given in Section 5.1 may be tentatively answered. First, FDC's commentary and recommendations on cracking that may occur at fatigue-susceptible details could be compared to the types of fatigue cracking that was known to have occurred on the in-service structure, revealing whether or not the system would predict the "correct" trouble spots. Second, FDC's evaluation of an in-service bridge could be compared to the evaluation of the system's domain expert to determine if a faithful ("consistent") representation of his knowledge exists. The answer to the final question, relating to the performance of the knowledge representation scheme, is dependent on the on-going evaluation by practitioners and experts.

The existing structures utilized as test cases for FDC served as two different types of tests, validation cases and field studies. As validation cases, the tests were primarily used to demonstrate the functionality of individual modules within FDC. As field studies, they were used to show the correctness and consistency of an FDC evaluation and the overall viability of the system as a tool. The different validation cases are given in Appendix C. In the validation cases, some input in held invariant, while other input is varied, providing an ordered, systematic check of the system [Chen 88]. The different field studies selected for FDC, and the results obtained, are described in the following sections.

5.4 Field Studies And Results

5.4.1 Canoe Creek Bridge

5.4.1.1 Description Of The Structure

The Canoe Creek Bridge, built in the 1960's, is located on Interstate 80 in Clarion County, Pennsylvania. The structure consists of two separate bridges with identical geometry. Each bridge is a twin-girder, floorbeam structure with five continuous spans, with span lengths up to 162 feet. The haunched main members are welded plate girders with varying dimensions over the length of the spans. In addition to the girders and floorbeams, a bottom lateral bracing system, connected with gusset plates to the girder web, exists on the structure. A cross-section view of the Canoe Creek Bridge is provided in Figure 5.1.

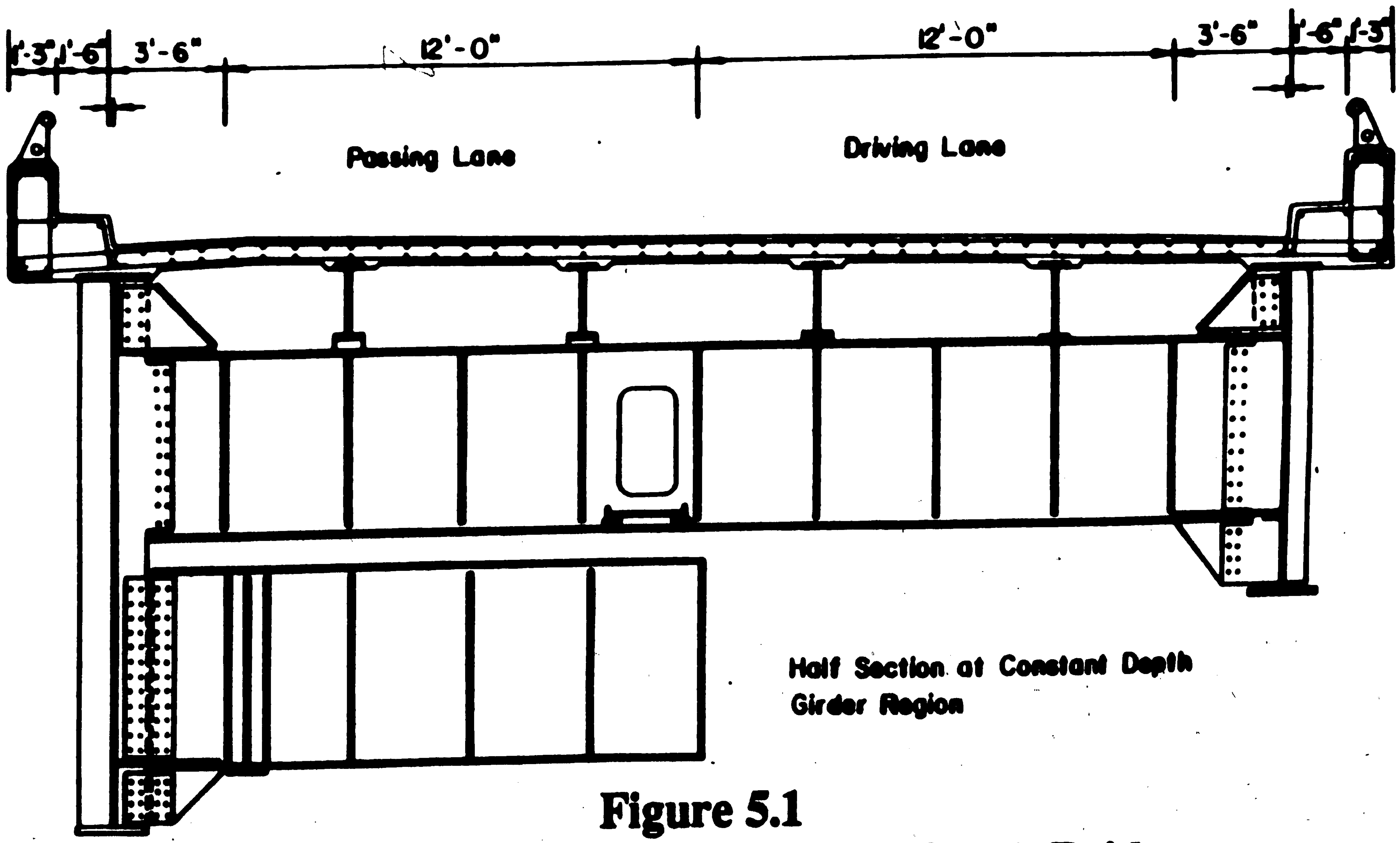


Figure 5.1
Cross-section View Of The Canoe Creek Bridge

A field examination of the structure revealed evidence of fatigue cracking in four locations in the main girder web: in the vertical gap at the bottom end of the floorbeam connection plates, in the horizontal gap between the lateral gusset plates and floorbeam connection plates, in the vertical gap at the top end of the floorbeam connection plates in the negative moment region, and at the ends of the lateral connection plate tabs welded to the girder web [Fisher et. al. 86]. These types of cracking are prime examples resulting from distortion-induced fatigue, which is not covered in design provisions, and therefore provide a good test of FDC's capabilities.

A partial interactive session on FDC for the Canoe Creek Bridge is provided in Appendix D. The portions of the session provided relate to the performance of those details experiencing cracking on the existing structure.

5.4.1.2 Discussion Of Results Obtained For Canoe Creek

The commentary and recommendations provided by FDC, at both the macro-parameter and detail design levels of operation, point to deficiencies in the Canoe Creek Bridge design which may have resulted in the fatigue cracking which exists on the structure. Within the macro-parameter commentary level, the system evaluation revealed that fatigue problems may occur at lateral gusset plates due to the lack of composite action between the girders and deck, which would allow increased differential deflection of the main girders. In addition, the fact that higher stresses often develop in the negative moment regions of continuous structures was pointed out. This condition could cause fatigue problems in the negative moment region, a case which actually occurred on the Canoe Creek structure, at the web gap at the top end of the floorbeam connection plates [Fisher et. al. 86].

Within the detail design portion of FDC, the system evaluation of the four details experiencing fatigue cracking on the Canoe Creek Bridge revealed that each of these details were susceptible to fatigue problems, and were not recommended for use by FDC. The gaps which existed at the bottom end of the floorbeam connection plates in the positive moment region, and at the top end of the floorbeam connection plates in the negative moment region, were designated as potential problem areas by FDC, and the system recommended that the gaps should be eliminated by using positive attachments. The fatigue cracking which occurred on the Canoe Creek Bridge at the lateral gusset plates (both at the gusset connection to the girder web, and at the intersection of the gusset and floorbeam connection plates) were predicted by FDC in its evaluation. It should be noted that the system not only pointed to the deficiency of a detail's design at the point in the design process when it was selected, but also indicated in previous stages that problems may be encountered. An example of this can be seen at the selection of the type of lateral system to be used. When a web lateral system was selected, FDC recommended that this system should be placed at the girder flange, and pointed out that web connections may be susceptible to fatigue problems. When the type of web connection was designated (fillet welding), the system pointed to the fatigue susceptibility of the detail and recommended a modification (i.e. that a bolted connection be used).

The Canoe Creek Bridge evaluation revealed that FDC was capable of predicting fatigue problems. In addition, it showed that the system could make recommendations and, if these recommendations were not taken by the user, would be able to point out potential problems, and make supplementary recommendations for the best way of handling the problems. For example, FDC recommended that a gusset / connection plate intersection be avoided. However, when the user rejected this recommendation, the system was capable of recommending a detail to handle this intersection which was best for fatigue performance. Finally, this test case shows that even selections or details not recommended by FDC often have positive aspects. This shows that the designer can weigh the positive and negative aspects of a selection himself, and choose to accept or reject the system's recommendation.

5.4.2 I-78 Delaware River Bridge

5.4.2.1 Description Of The Structure

The Delaware River Bridge, built in the late 1980's, is located on Interstate 78 between Pennsylvania and New Jersey. The structure is a dual, seven span continuous bridge, with spans ranging in length from 100 feet to 228 feet, and a total length of 1222 feet. There are four main welded plate girders on each bridge. There is no floorbeam / stringer or lateral bracing system on the structure, there are, however, diaphragms on the bridge. A cross-section view of the I-78 Delaware River Bridge is provided in Figure 5.2 on page 57.

Since the I-78 Delaware River Bridge was only recently constructed, there is no information on the in-service fatigue performance of the structure. Therefore, the field test for this bridge was an attempt to determine if there were any fatigue-critical details on the structure.

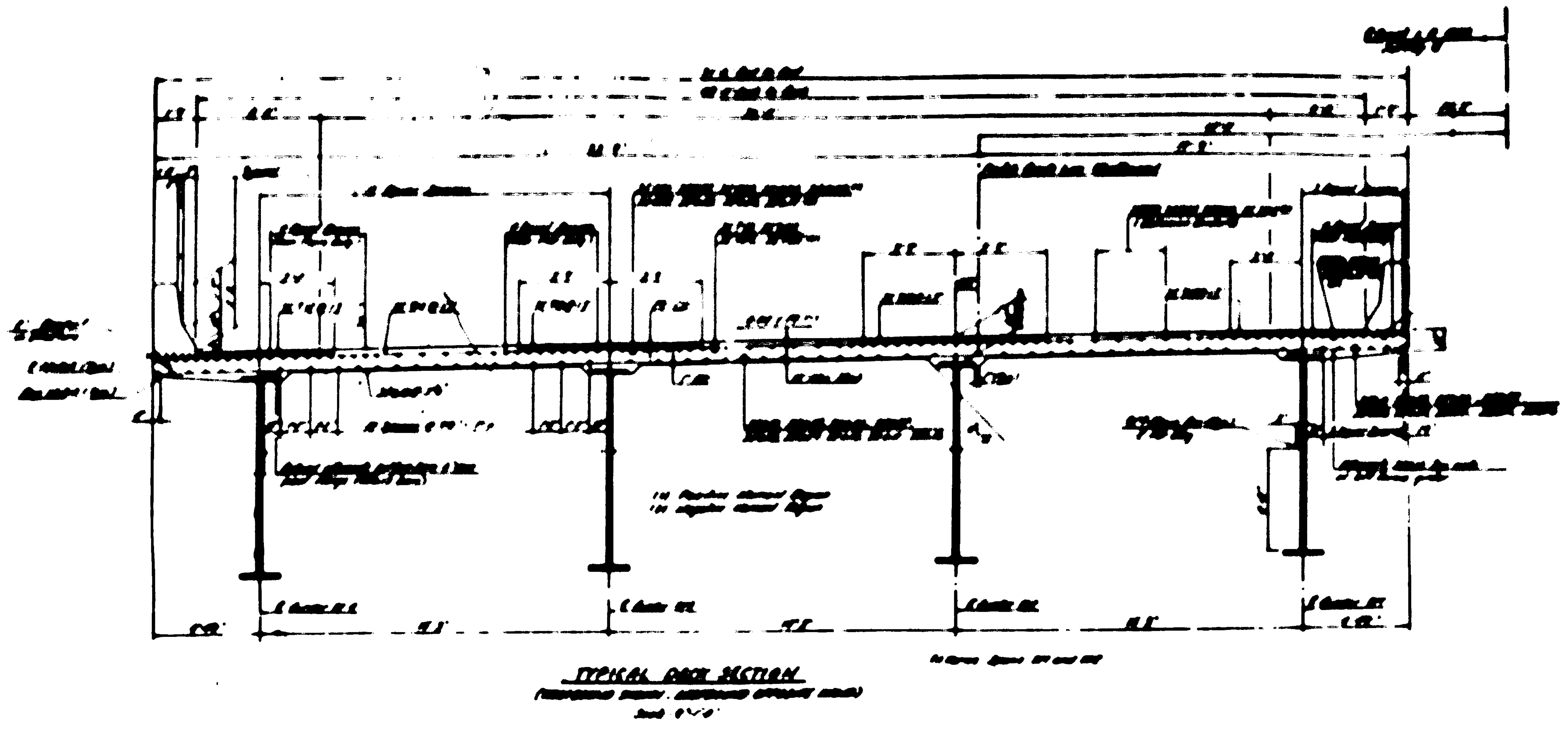


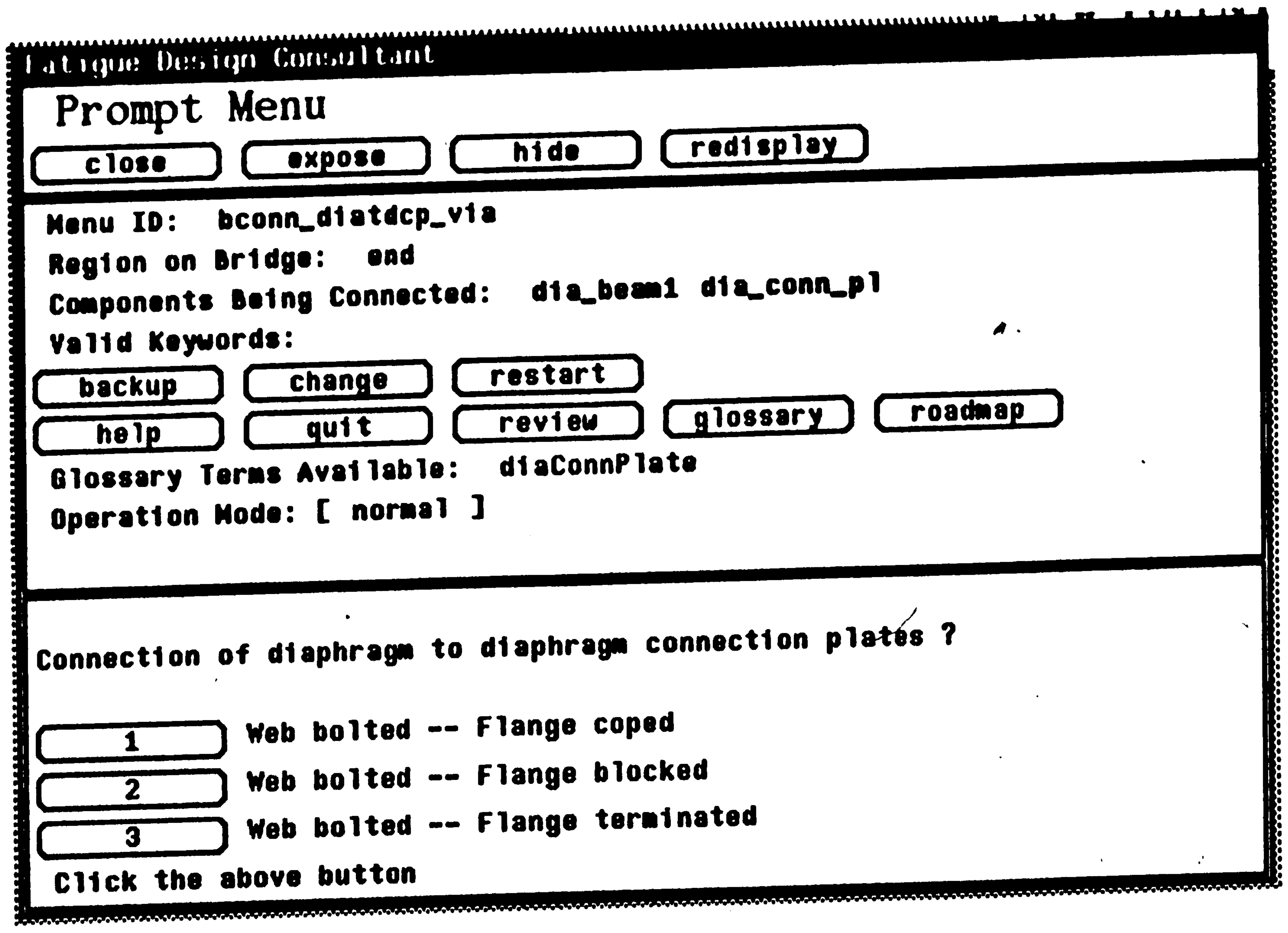
Figure 5.2
Cross-section View Of The I-78 Delaware River Bridge

A partial interactive session on FDC for the I-78 Delaware River Bridge is provided in Appendix E. Portions of this appendix will be referenced in the following section, a discussion of the results obtained in the FDC evaluation of the structure.

5.4.2.2 Discussion Of Results Obtained For I-78 Delaware River

This FDC evaluation of the I-78 Delaware River Bridge revealed that the structure was relatively free from details susceptible to distortion-induced fatigue cracking. Most of the macro-parameter and detail design selections for this design conformed to the recommendations made by the system. According to FDC, the bridge should, therefore, exhibit good fatigue performance. The only details targeted by the system as possibly being susceptible to fatigue damage were a number of the fillet welded connections (i.e. the main girder flange fillet welded to the girder web). The recommended alternatives were rather superficial, to use a bolted connection rather than a welded connection, if possible. There were, however, no extremely critical details, such as those specified in the Canoe Creek evaluation.

The FDC evaluation of the Delaware River Bridge did, however, reveal a deficiency in the system itself. It was realized during the evaluation, that the possibility exists that FDC does not always provide the user with an adequate list of possible selections to precisely describe the bridge to be evaluated. For example, when the user is given a list of possible options for the connection of the diaphragm to the diaphragm connection plate (shown in Figure 5.3), the option is not given for the diaphragm to be



```
Menu ID:  bconn_diatdcp_via
Region on Bridge:  end
Components Being Connected:  dia_beam1 dia_conn_pl
Valid Keywords:
Glossary Terms Available:  diaConnPlate
Operation Mode: [ normal ]

Connection of diaphragm to diaphragm connection plates ?

1  Web bolted -- Flange coped
2  Web bolted -- Flange blocked
3  Web bolted -- Flange terminated
Click the above button
```

Figure 5.3
Options Provided By FDC For Diaphragm To Connection Plate

welded to an additional connection plate which is, in turn, bolted to the diaphragm connection plate, a condition which exists on the Delaware River Bridge and which is shown in Figure 5.4.

This problem places the burden of making an assumption on the user. If the assumption he makes is not accurate, a fatigue problem, inconsistent with his structure's design, may be incorrectly predicted, or a potential fatigue problem may be missed. This situation indicates that more work on FDC is necessary to cover all possible bridge topology and connectivity possibilities, or to provide the user with the option of specifying that a specific detail or selection cannot be adequately described by the options provided by the system.

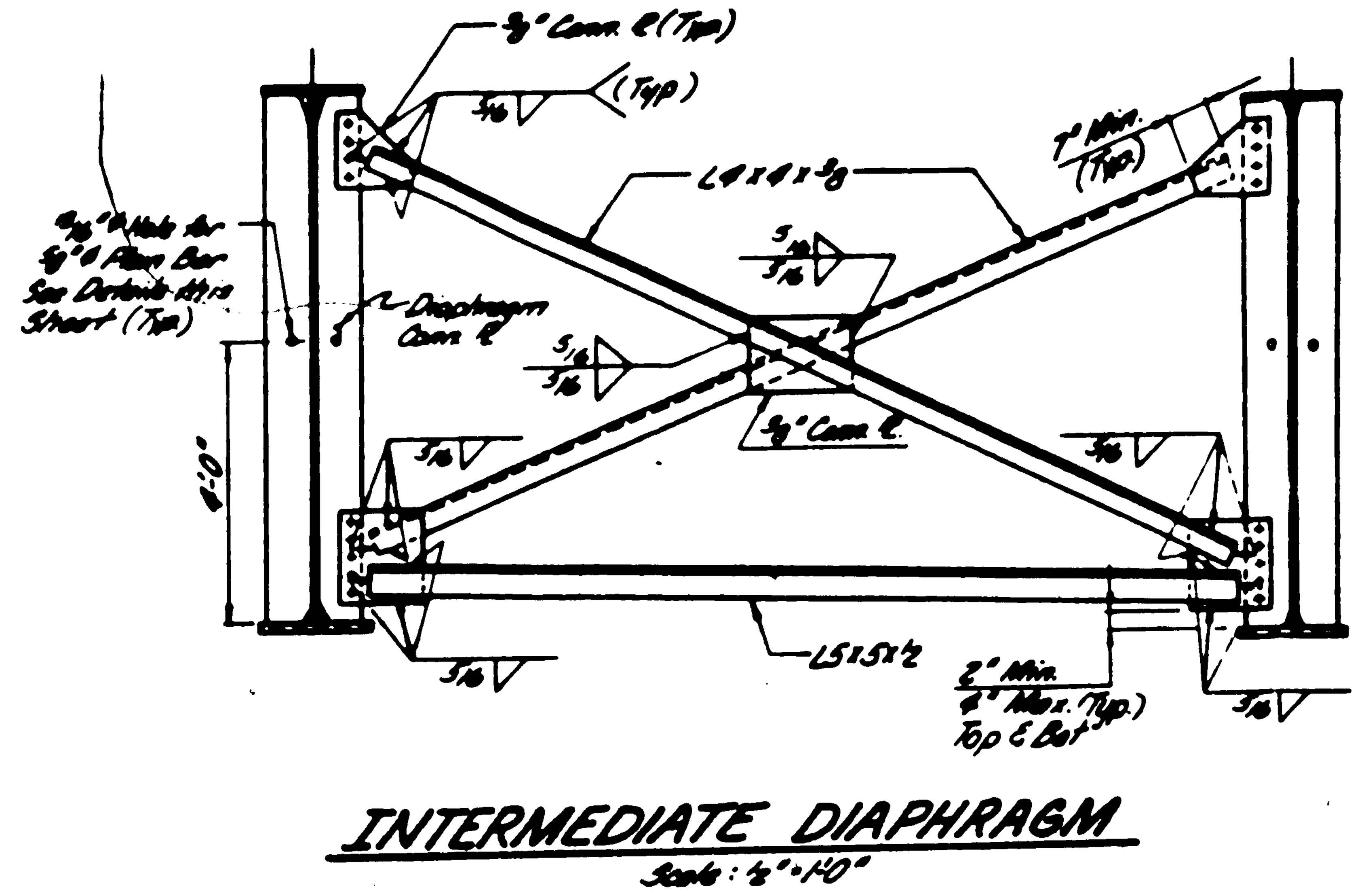


Figure 5.4
Typical Diaphragm Detail For I-78 Delaware River Bridge

5.5 Field Test Correlation With Human Expertise

The results of the Canoe Creek and Delaware River field tests indicate that the two structures should exhibit different calibres of fatigue performance. The Canoe Creek structure was determined by FDC to possess a number of serious design deficiencies which should adversely affect the bridge's fatigue performance, while the I-78 Delaware River bridge was determined to be relatively free from fatigue-susceptible characteristics. It was, however, necessary to compare the results obtained in the FDC evaluation with an evaluation of a human expert in the domain, to check the integrity of the system's results. These field tests had been acquired from the system's domain expert, with the request that he provide two designs, one that he considered a relatively "good" design, and another that he considered a relatively "poor" design. It was also requested that he not reveal which of the designs was good and which was poor [Fisher 90].

After the field tests were run on FDC, the expert revealed that, in agreement with FDC, the Canoe Creek design was considered to be highly susceptible to many fatigue problems, and that the Delaware River design could be expected to perform fairly well for fatigue considerations. For the Canoe Creek structure, much of the detection and evaluation of the actual cracking that occurred on the structure was determined by the domain expert. The cracking, which was found by the expert, was also predicted by FDC. The commentary and recommendations provided by FDC for these problem details were reviewed by the expert and determined to be appropriate. For the Delaware River Bridge, the expert revealed that he could foresee no major distortion-induced fatigue problems occurring. This, too, was in agreement with the evaluation provided by FDC.

While the results obtained with FDC for these two field studies correlated well with the opinion of the domain expert, they cannot be considered a complete, comprehensive test of the system. The positive correlation with a human expert for these two tests does not, of course, guarantee a positive correlation in all cases. In addition, the tests that were run, because they were provided by the expert himself, may not be a completely objective test. Finally, even if consistency of the system and the domain expert occurs, there is no guarantee that both of the evaluations, system and human, may have faults. All of these factors indicate that extensive testing of such a knowledge-based system, which addresses a complex, real-world problem, is necessary, and that a more comprehensive evaluation of the capabilities and effectiveness of the system can only be achieved as the system is actually used.

6. Conclusions

6.1 Contributions

6.1.1 Knowledge In The Domain

While the development of FDC did not entail research into the generation of new concepts of fatigue and fracture, the system does represent a new manner of formalizing and representing some of the knowledge that already exists in the domain. An attempt was made to produce a more comprehensible body of knowledge from the rather disjoint collection of existing heuristics and rules-of-thumb. This knowledge was formulated in a way that could be more readily applied to the solution of real problems in the domain. It particularly addressed the interaction of different parameters within the domain, and provided a means of formulating a more rational methodology for the qualitative design of bridge parameters and details for the effects of fatigue.

In addition to the formulation of the knowledge base, the development of FDC raised a number of relevant issues concerning the current design procedure used in practice. Firstly, the development pointed to the ineffectiveness of current design procedures to address the problem of the design of bridge details for the effects of fatigue. It pointed to the need for a modified design procedure that, even if FDC were not used, would place a greater emphasis on the design of bridge details, and the relationships between these details. Also, the development of the system was a direct result of the lack of formalized guidelines or codes to deal with the problem of fatigue, specifically distortion-induced fatigue and problems emanating from initial flaws. This suggested that additional research in the domain would be necessary to establish these guidelines. Finally, the development of FDC pointed to the need for better training and education of bridge designers in the domain of fatigue and fracture. The system represents a means of helping to improve the education of the designers by disseminating the knowledge of experts in the domain so that it can be brought to bear in the solution of real-world problems.

6.1.2 Knowledge Formalization

The development of FDC not only resulted in an approach being adopted for the formulation of knowledge in the domain into a coherent framework, but also provided a test case for the implementation of this framework within an open-system architecture. The attempt to develop a second-generation knowledge-based system, based on a deeper model of reasoning, pointed to the need for the adoption of this type of deeper model in the conventional design procedure. Also, the development of the system attempted to address the problems that could be encountered in a dynamic knowledge domain, such as the influx of new knowledge, and the necessity of dealing with incomplete knowledge within the design process.

Finally, the development of FDC provided a means of testing the validity of the open-system framework. By being able to produce a new scenario module within the domain of an existing knowledge-based system, and effectively link this module to an existing knowledge core, it was determined that the open-system framework provided a viable means of extending knowledge-based systems within a particular domain. Further, since this extension was accomplished in a relatively short amount of time, and with little modification to the existing knowledge core, it pointed to the effectiveness of the open-system framework in the development of new knowledge-based systems.

6.2 Development Concerns

A primary concern in the development of the system resulted from the fact that FDC was implemented as a scenario module, and is therefore dependent on the core knowledge and system utilities, of BFI. This means that if errors exist within relevant portions of BFI, their effects could manifest themselves in the use of FDC. This dependence of individual scenarios on a pre-established core, and the possibility of the trickle-down of errors is an inherent weakness of the open-system architecture. This problem is most critical when a new scenario module, such as FDC, is developed by someone other than the developer of the knowledge core. While the development of a scenario module without some knowledge of the structure and contents of the core and utilities is infeasible, someone with a limited understanding of these, capable of developing a scenario module, may still not understand all the nuances of the existing framework and the knowledge content. This could present problems with the debugging of errors, or may result in inconsistencies between the core and scenario knowledge.

Perhaps the most important concerns in the development of FDC deal with the validity and maintenance of system knowledge. A number of distinct problem areas exist. The way in which these problems were addressed within FDC, along with the shortcomings of these solutions are presented below. Also presented are some solutions which were not implemented in the FDC prototype, but which are possible alternatives for future enhancement of the system.

The most easily resolved concern dealt with the existence of contradictory expert opinions. Since the problem domain is highly subjective, it is inevitable that different experts may have different opinions on certain matters. Within FDC, this problem was eliminated by using only one domain expert as the primary source of knowledge within the system. While more than one expert and reference was consulted, when differences of opinion existed, the primary expert's opinion was used. An alternative, not utilized in FDC, is the use of multiple experts, where different expert opinions are presented, and the user is able to select which expert's advice he wishes to use. This, however, may result in inconsistencies in the system's commentary and recommendations if the user elects to consult different experts at different stages of operation. A potential problem in FDC, as yet unresolved, results from one of the basic requirements of a well-designed KBS, the capability of the system to allow the user to plug his own knowledge or rules into the system. This capability would allow the system to be customized for the practices or procedures of the user. However, if the user's rules contradict those of the expert, the whole system may become inconsistent or unreliable. However, it is not within the scope of this research to examine conflict resolution strategies.

The next concern dealt with the fact that incomplete knowledge will exist at a particular stages of the bridge design process. For example, some quantitative parameter, yet to be calculated, may affect the selection of a qualitative detail. This may prevent the system from making a complete evaluation of the situation. Possible solutions to this problem include having the system dynamically modify its query pattern to attempt to ascertain the needed information from the user. If this includes quantitative calculations, procedural attachments to the system may be necessary. However, this approach could be undermined if the designer is unsure of the information himself, or if the quantitative calculations could not be performed at this stage of the design. The approach taken in FDC is to point out to the designer the type of information the system would need to make a complete evaluation (allowing him to see what factors influence the decision). In addition, the system recommends the best alternative for fatigue performance based on the information which is known. The designer can later determine if this recommended alternative is feasible and suitable (i.e. after the designer has calculated the unknown quantitative parameters). Ideally, the system would make this first, best-guess recommendation, and as new knowledge is entered into the system, update these recommendations to reflect the influence of the new information. This idealized operating scheme has not yet been implemented in the system (but is a possible system enhancement), which may make it necessary for the user to cycle through the design procedure.

Perhaps the most critical issue, and most enlightening to the developer of this knowledge-based system, deals with the growth or updating of knowledge within the domain. What is accepted as state-of-the-art expert knowledge at the present time , and therefore incorporated in the system, may become outdated or completely unacceptable in light of knowledge that results from future research in the domain. A "good" knowledge-based system should be able to accommodate the updating of knowledge, however a problem exists. This problem may manifest itself as a triviality, if the new knowledge has little bearing on other knowledge within the system, or as an impasse, if the new knowledge is a fundamental building block of the knowledge base with dependencies that affect virtually every aspect of the system's operation.

If a relatively isolated piece of knowledge, this information can readily be incorporated into the system with, perhaps, as little as the modification of a single rule. However, if the outdated knowledge is so intertwined within the knowledge base that changing it could result in widespread inconsistencies, the system may be rendered useless. This problem pointed to the need for a deeper model-based (causal) reasoning scheme, in general, and helped lead to the development of the Design Dependency hierarchy used in FDC.

The way in which this problem was addressed in FDC, and by no means to be considered a perfect solution, was to structure the knowledge from what seemed to be the most well-established (in the opinion of the domain expert) base. This base represented the fundamental relationships between the individual components or details within the design, and was organized as the system's Design Dependency network. Other knowledge, considered less reliable or established, was used to fill in the gaps, or make specific recommendations rather than serve as a fundamental piece of knowledge.

This approach was tested during the development of FDC. One of the fundamental pieces of knowledge within the system stated, that if at all possible, the use of a bottom lateral bracing system should be avoided, because there are not only many fatigue problems with this type of bridge component, but the use of such a bracing system affects many other details used on the bridge. One of the supplementary pieces of knowledge within the system, dealing with the use of a bottom lateral bracing system, was used to determine if this type of bracing would be required for a specific bridge. After this information had been incorporated into the FDC prototype, it was found that the piece of knowledge dealing with the required use of a bottom lateral bracing system had become outdated, because a new guideline was now being used in practice. The incorporation of this new knowledge resulted in the situation being created that, at the stage in FDC where the user decides whether or not a bottom lateral bracing system is to be used, there would be incomplete knowledge within the system to make a concrete determination of whether or not the bottom lateral bracing was required. FDC must therefore make the best recommendation it can with the known information. This, however, is a minor problem compared to the effects that would have resulted if the fundamental concept, that use of a bottom lateral bracing system should be avoided if possible, would have changed.

Therefore, while the knowledge framework in FDC remained, in this case, fairly unchanged with the addition of a new piece of information, it cannot be assumed that other new knowledge can be so easily incorporated. The possibility exists, that at some time in the future, new knowledge may be uncovered that would so radically alter the framework of the knowledge within FDC, that it would be more viable to scrap the system and make a fresh start. While the developer of FDC recognizes this fact, he believes that this problem is not unique to FDC, and may in fact be common to all knowledge-based systems that attempt to address a complex real-world problem situation.

6.3 System Impact

6.3.1 In Education

The commentary and recommendations given to the user by FDC are perhaps most useful as a teaching tool for the student of bridge design. They provide the student with the opportunity of seeing how different design choices may affect the fatigue performance of bridges. Often, courses which teach the fundamentals of bridge design deal only with the determination of loads and the sizing of main members, and neglect the design of details and connections, where the majority of fatigue problems occur. Also, as opposed to a passive textbook which may simply attempt to address fatigue within isolated details, FDC looks at the interaction of different details on a particular bridge. The system allows the student to experiment with his design, to test different combinations of details and learn how these selections and details are interwoven. The student is also exposed to the reasoning and knowledge of an expert in the field, which allows him to learn the type of decisions an expert would make when confronted with a particular decision.

6.3.2 In Professional Practice

While FDC, in its present form, is most suited to use in an educational environment, it could be made more suitable for use in a professional environment. By incorporating specific practices in FDC, the system can help train the novice designer in the practices of his firm. In addition, the system, which at present utilizes the accepted bridge codes in a limited form, could be extended to reference pertinent bridge code sections, along with commentary, when it is appropriate. The system could therefore be utilized as an on-line design reference as well as a design aid. All of these factors, along with the system's ability to help generate fatigue-resistant bridge designs, help to make FDC a potential tool for the practicing professional. However, it is important to note that the problems that could result from new, changing, or incomplete knowledge, along with the need for the critique of a bridge design from multiple viewpoints, should be addressed before the system can be considered suitable for professional use.

6.4 Personal Gains

The development of the FDC prototype system provided the system developer with a new perspective of the formulation and solution of complex problems. While the solution of textbook examples and the development of toy systems to address simplistic problems are relatively straightforward, the formulation and solution of complex real-world problems is a much more formidable task. It became apparent that it was necessary to accept the fact that well-established guidelines for the solution of a particular problem did not always exist. In addition, it was necessary for the developer to learn to accept the possibilities of an ever-changing domain and the existence of incomplete or uncertain knowledge, and then develop a rational means of dealing with these problems. Through the development process and the attempted solution of some of these problems, that the developer got a feel for what engineering really is, not just calculations and cookbook solutions, but the formalization and solution of problems riddled with uncertainties, where educated assumptions and trade-offs have to be made.

The system developer realized that, even though he was a structural engineer with some background in the domain, there was a great deal of knowledge that was concentrated solely in the hands of the experts in the field. Further, that even the experts did not always possess a formal scheme of reasoning, with their decisions often based on experience. By developing the FDC system, a great deal of knowledge on both the fatigue and fracture of steel bridges, as well as the bridge design process, was attained. Along with this knowledge, came the realization that more research was necessary, both to increase the knowledge in the domain and to formalize and represent it in a form that can be used in the profession.

Perhaps the most important things learned by the developer during the formalization of the problem and the implementation of FDC were the ways in which the solution of any problem could be attacked. Specifically, that complex problems could be broken down into simpler subtasks which were easier to address. In addition, it was realized that the need to organize the problem, and the information available to solve it, was of paramount importance. By doing so, the factors which influence the problem and solution, as well as the relationships between different parts of the problem can be better understood.

The actual computer implementation of the FDC system presented numerous problems to the system's developer, who was not a computer programmer or computer scientist, and had virtually no experience with knowledge-based systems. It was found that actually learning the computer language necessary for coding FDC was relatively simple, however, building the code in a form which could be linked to the existing program (BFI) was not easy. Difficulty arose from the need to understand the code that already existed within the BFI system. This illustrated to the developer the importance of properly documenting code. However, it was learned that while commentary and documentation can help, it can not pass along the reasoning behind coding decisions, or explain all of the nuances of the code. While personal communication with the developers of the original BFI code was helpful, the problem was reciprocal, in that they did not necessarily understand exactly how FDC was being coded.

The computer implementation of FDC did, however, convince the developer of the viability of the knowledge-based systems approach to the solution of complex real-world problems, specifically, when these systems are constructed in an open-system framework. Being an engineer in the problem domain, and being able to conceptualize, organize, and implement a prototype knowledge-based system in the span of a few months, proved to the developer that these type of systems could be readily constructed and applied. Further, that this development could be undertaken by those who understand the problem domain, and not relegated to those adept only at computer programming. This fact allows for a computer implementation which can more faithfully represent the problem and solution. While it is realized that knowledge-based systems can never replace the human experts that they are intended to model, they can serve to transfer useful knowledge to the practicing professional.

7. Enhancements and Extensions

7.1 Enhancements

It is believed that the FDC prototype, in its current form, can serve to prove the viability of the knowledge-based systems approach to the solution of problems in the domain of fatigue and how it relates to bridge design. In addition, it is believed that the prototype system can be utilized as a practical tool to help address the problem of fatigue-susceptible bridge designs. However, it is also felt that certain enhancements could improve the efficiency and effectiveness of the system in achieving its goals. These enhancements were realized during the conception, implementation, and testing of FDC, and provide a platform for possible future research and development.

A number of the possible enhancements relate to the nature and usefulness of the information the system passes along to the user. The first enhancement would involve improvement of FDC's explanation facilities to more accurately reflect the knowledge in the knowledge base, and how this knowledge was utilized to arrive at a particular solution. This would be accomplished by allowing the user to see the inferencing process that the system went through to determine the appropriate commentary and recommendations. The importance of providing the system with the ability to capture and display its inferencing process is described below [Wong and Wilson 89].

> "Ability to display reasoning steps of the system in lieu of treating it as a mere "black box" is an essential feature to put the system to field use. It makes explicit possible logical faults or inconsistencies in the knowledge-based system. It provides

> the user with dynamic views of the reasoning strategy as it is instantiated during the problem solving process. The criterion also helps technology transfer through the addition of a computer-aid instruction facility into the existing knowledge base."

It is important to note that if this capability were to be incorporated into FDC, the inferencing process presented to the user would have to be in a form which he could easily understand, and not just as a listing of the system inferences in computer code.

Another enhancement would allow the system to present information to the user at different levels of abstraction or detail. This would allow the beginner to receive more simplistic explanations, while the more experienced bridge designer could be given more detailed, complex information. This capability would improve the educational aspect of the system by allowing the user to operate the system at increasing levels of expertise as his own knowledge increases. The beginner would not be mired in an overwhelming amount of complex information, and the more experienced user would not be bored with basic information which was not useful to him.

Additional improvement of the explanation facilities would result if the system's graphics capabilities were upgraded. This could include providing graphical representations of the type of fatigue cracking that could be expected if certain design decisions were to be made. One possibility involves the incorporation of Integrated Imaging and Optical Scanning techniques to allow the user to see displays of actual cracking on existing structures that have different structural configurations. Textual descriptions of possible ramifications of different design selections may be made more convincing if the user could see examples of the type of damage that could result. Many engineers think visually, and knowledge-based systems can be most effective when they present complementary graphic and verbal information to the user or learner [Wilson et al. 88]. The use of graphics could also be extended to provide the user with a more accurate description of alternatives recommended by the system.

In addition to the information currently available to the user in FDC, additional information could be provided. One possibility is the inclusion of pertinent design code sections, or references to these sections. This type of information would be most useful in a professional environment, where the codes may govern calculations needed to be performed by the user before specific design decisions can be made. While some referencing of design codes is currently performed by FDC, this capability has not been fully implemented (In fact, it may be difficult to provide this capability because of the different practices that exist throughout the U.S.).

7.2 Extensions

In addition to the enhancements that could be performed within the current scope and framework of FDC, a number of possible extensions of the system exist. These extensions would modify the environment in which FDC could be employed, the applications which could be addressed, or the format of the user interface. Most of these extensions would entail changes to the framework of FDC, and the addition of new knowledge to the system's knowledge base. It should be noted that each of these extensions may require a relatively large amount of work, and may be a lengthy task to perform.

FDC could be extended to operate in the quantitative phases of the design process.

As stated before, the prototype system focuses on the selection of general bridge parameters and the preliminary qualitative design of details. FDC could be linked to algorithmic programs which perform the computation of loads imposed on the structure, and the sizing of members and connections. In addition, a quantitative fatigue model could be included in the system which, along with a structural analysis package, would be able to compute the estimated fatigue life of specific details. It is surmised that this extension to quantitative design would entail a great amount of modification to the current system framework, and could result in an explosion in the size and complexity of the system. It would, however, help make the system more suitable and attractive for use in a professional environment.

Another extension would allow for the critique of a proposed bridge design from multiple viewpoints. While the current system provides a critique from the perspective of fatigue performance, the design could also be assessed for other considerations such as fabricability, erectability, and cost. These factors could then be weighed to provide an overall estimate of the design. This is another extension which would make FDC a more viable approach to design within the professional environment.

It is also possible to extend the scope of the FDC system to include the design of bridge types other than steel I-girder bridges (the only type currently addressed in the system). Extending the scope of FDC to serve this purpose alone should not require modification of the current system framework. However, the information on the fatigue performance of any other bridge type would have to be formalized in a manner similar to that used for steel I-girder bridges. It should be noted that the benefits of this type of extension may not warrant the amount of work necessary to perform it. If a different bridge type constitutes only a small fraction of the structures utilized on the highway system, or if fatigue problems associated with the different bridge type are minimal, then the extension may not be suitable.

Other possible extensions would involve modifications to the FDC user-interface. The system could be put into a Hypermedia type operating environment [Harvey 89], which is well-suited to achieving the educational goals of FDC. In addition, some of the capabilities of the Knowledge-Base Editor (Section 4.4) which have not been incorporated into the system could be implemented. These extensions could help produce an operating environment which is more conducive to use of FDC, and which provides for the more efficient transfer of information to the user.

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Appendix A

Summary of Types of Bridge Details Experiencing Cracking

Summary of Types of Bridge Details Experiencing Cracking

DETAIL	INITIAL DEFECT OR CONDITION	NUMBER OF BRIDGES	FATIGUE CATEGORY
1. Eyebars	Stress Corrosion	1	---------
	Forge Laps, Unknown Defects	12	Initial Crack
2. Anchorage Eyebars	Corrosion Notching and Pin Fixity	1	---------
3. Pin and Hanger Assemblies	Frozen Pins	2	Out-Of-Plane
	Partial Bearing	1	Corrosion Packout
	Pin Fixity (Corrosion Packout)	1	Rivet Hole
	Other	1	D
4. Verticals (Hangers) (Truss and Arches)	Vibration-Wind	4	Aeroelastic Instability
5. Coverplated Beams	Normal Weld Toe	5	E'
	Fabrication Cracks	1	<E'
6. Flange Gussets	Weld Toe	8	E or E'
7. Web Gusset	Intersecting Welds	6	<E'
	Weld Termination	2	<E
	Gap Between Stiffener and Gusset	7	Out-Of-Plane
8. Gusset Plates	Lateral Bracing Vibration	3	Out-Of-Plane
9. Flange or Web Groove Weld	Lack of Fusion	7	Large Initial Crack

DETAIL	INITIAL DEFECT OR CONDITION	NUMBER OF BRIDGES	FATIGUE CATEGORY
10. Coverplate Groove Welds	Lack of Fusion	4	Large Initial Crack
11. Web-Flange Fillet Weld at Curved Haunch	Lack of Fusion	1	Initial Crack
12. Web-Flange Welds	Transverse Weld Cold Cracks or Internal Flaws	2	Initial Crack
13. Box Girder Beam to Box Girder Column Welds	Lack of Fusion in Closure Plates	1	Initial Crack
14. Box Girder Corner Welds	Transverse Weld Cold Cracks	3	Large Initial Crack
15. Web Gap Distortion at Internal Diaphragm	Lack of Fusion at Back-up Bar	2	Initial Crack
16. Longitudinal Stiffeners	Lack of Fusion, Poor Weld	8	Large Initial Crack
	Weld Termination	1	<E
	Web Gap	1	Out-Of-Plane
17. Electroslag Welds	Various Flaws	6	---------
18. Plug Welds	Crack	1	---------
19. Welded Repair	Lack of Fusion Weld Termination	3	<E
20. Welded Web Inserts	Lack of Fusion	2	Large Initial Crack
21. Welded Holes	Lack of Fusion	3	Large Initial Crack

DETAIL	INITIAL DEFECT OR CONDITION	NUMBER OF BRIDGES	FATIGUE CATEGORY
22. Flanges and Brackets Through Web	Flange Tip Crack	3	<E'
23. Rivet Head	Prying	2	Prying
24. Lamellar Tearing	Restraint	2	---------
25. Bearing Stiffener	Web Buckling	1	Out-Of-Plane
26. Girder Web	Welding Discontinuities at Temporary Attachments	1	<E
27. Double Connection Angles	Restraint in Connection	2	Out-Of-Plane
28. Back-up Bar	Back-up Bar Butt Splice, Lack of Fusion	2	<E'
29. Transverse Stiffeners	Shipping and Handling	8	Out-Of-Plane
	Web Gap	1	Out-Of-Plane
30. Floorbeam Connection Plates	Welded Girder Web Gaps	31	Out-Of-Plane
	Riveted Web Gaps	1	Out-Of-Plane
31. Floorbeam and Cantilever Bracket Connection Plates	Restraint	4	Out-Of-Plane
32. Floorbeam and Cantilever Bracket Webs at Connection Plates	Web Gap	3	Out-Of-Plane
	Welded Vertical Connection Plate	1	Out-Of-Plane

DETAIL	INITIAL DEFECT OR CONDITION	NUMBER OF BRIDGES	FATIGUE CATEGORY
33. Diaphragm Connection Plates	Lack Of Fusion Web Weld	3	Initial Crack
	Web Gaps	18	Out-Of-Plane
	Box Girder Web Gaps	7	Out-Of-Plane
34. Diaphragm and Floorbeam Connection Plates at Piers	Web Gaps	4	Restraint
35. Box Girder Flange-Diaphragm Connection Plate Weld	Lack of Fusion, Weld Termination, Poor Quality Welds	1	<E'
36. Stringer-Floorbeam Brackets	Web Gap	4	Out-Of-Plane
37. Stringer End Connections	Restraint	3	Weld Termination
38. Tied Arch Floorbeams	Web Gaps	8	Out-Of-Plane
39. Tied Arch Floorbeam Connections	Weld Root	2	Restraint
40. Coped Members	Notch and Restraint	21	Flame Cut Edge
	Notch and Restraint	2	Out-Of-Plane
41. Compression Flange Attachment	Cross Bending of Flange	1	E'
42. Compression Flange - Diaphragm Connection Plates and Weld Toe	Overstressed Weld	2	Residual Stress

Appendix B

FDC Design Dependencies

FDC
Hierarchy of Design Dependencies

1	Main Girder Configuration						
2	A2	Lateral Bracing System					
3	A3	B3	Stiffener Configuratio				
4	A4	B4	C4	Floorbeam Configuratio			
5	A5	B5	C5	D5	Diaphragm System		
6	A6	B6	C6	D6	E6	Stringer Configuratio	
7	A7	B7	C7	D7	E7	F7	Stringer Diaphragms
	A	B	C	D	E	F	G

A1 Main Girder Configuration

Choices to be made:

- Number of Main Girders
- Span Length
- Girder type - Rolled vs. Built-up
  - If Rolled - Coverplates Used ?
  - If Built-Up - Stiffeners Used ?
- Layout - Right vs. Skew
- Deck Action
- Suspended Span Used
- Splices Used

A2

Influence of Main Girder Configuration on Lateral Bracing System

- If span length meets certain code requirements, no lateral bracing system is required. However, if there are only 2 main girders a lateral system should be used to improve the redundancy of the structure.

- If the girder is composite with the deck, a top lateral bracing system is not required, because the deck serves to provide lateral stability to the top flange. Composite action also tends to minimize the differential deflection of the girders.

- If differential deflection is great, problems at the lateral gusset plate connection will be worsened

- Possible causes of differential deflection:
    - No composite action
    - Skew bridges are susceptible to more severe diff. deflection

A3

Influence of Main Girder Configuration on Stiffener Configuration

- Type of girder will help determine the type and number of stiffeners required.
    - Rolled Main Girders - No stiffeners used
    - Built-up Main Girders - Stiffeners may be used
- If girders are built-up, then the number and type of stiffeners depends on the size of girders, i.e the plate thicknesses.

A4

Influence of Main Girder Configuration on Floorbeam Configuration

- If there are more than 4 main girders there will be no floorbeams

- Differential deflection of main girders could cause problems at floorbeam connection to girders.

    - Due to skewness
    - Because there is no composite action between girder and deck

- If cantilever floorbeam brackets are used:

    - Relative movement between girder and slab or changes in girder curvature could result in high bending stresses developing in cantilever bracket tie plates.

    - Differential rotation of girders and floor system will worsen problems at cantilever brackets, therefore embedding girder and floorbeam flange in deck may eliminate the problem.

A5

Influence of Main Girder Configuration on Diaphragm System

- Diaphragm size should be:
    - 1/3 to 1/2 depth of rolled main girder
    - 1/2 to 3/4 depth of built-up main girder
- Differential deflection of main girders could cause problems at diaphragm connection to girder.
    - Due to skewness
    - Because there is no composite action between girder and deck

A6

Influence of Main Girder Configuration on Stringer Configuration

- If there are more than 4 main girders, there will be no stringers

A7

Influence of Main Girder Configuration on Stringer Diaphragms

- If there are more than 4 main girders, there will be no stringer diaphragms

B2 Lateral Bracing System

Choices to be made:

- Use of Lateral Bracing System
- Position of Lateral Bracing System (Top/Bottom/Both)
- Type of Attachment to Girder
- Region on Bridge (Moment Region)
- Intersection With Other Members (i.e. Stiffeners or Connection Plates)

B3

Influence of Lateral Bracing System on Stiffener Configuration

- If possible lateral system should be bolted to the girder flange.

- If a flange connection for the lateral system is not to be used and the lateral bracing system does not intersect transverse stiffeners, then a web gusset plate should be used for the lateral bracing system set 6" to 12" above flange, and proper gap lengths should be maintained in connecting laterals to gusset plate.

- If the lateral bracing system does intersect transverse stiffeners, then the stiffener should not be used as a connection plate for transverse members. In addition:

    - Positive attachment of gusset plate and stiffener is recommended with proper gap distances maintained.

    - Only one gusset plate should be used and intersecting welds should be avoided.

    - In positive moment region, transverse stiffener should be sut short, and in negative moment regions and over supports transverse stiffener should be welded to flange.

- If the lateral bracing system intersects a stiffener used as a connection plate, then the connection plate must be attached to both girder flanges.

B4

Influence of Lateral Bracing System on Floorbeam Configuration

- If lateral bracing system intersects a floorbeam connection plate, it is recommended that a positive attachment between the connection plate and gusset plate be made.
- If lateral bracing system intersects a floorbeam connection plate, it is recommended that the lateral members be positively attached to the connection plate also.
- In addition, only one gusset plate should be used, and intersecting welds avoided.
- If the lateral bracing system intersects the floorbeam connection plate, then the floorbeam connection plate must be connected to both girder flanges.

B5

Influence of Lateral Bracing System on Diaphragm System

- If lateral bracing system intersects a diaphragm connection plate, it is recommended that a positive attachment between the connection plate and gusset plate be made.
- If lateral bracing system intersects a diaphragm connection plate, it is recommended that the diaphragm members be positively attached to the connection plate also.
- In addition, only one gusset plate should be used, and intersecting welds avoided.
- If the lateral bracing system intersects the diaphragm connection plate, then the diaphragm connection plate must be connected to both girder flanges.

B6

Influence of Lateral Bracing System on Stringer Configuration

No Direct Influence

B7

Influence of Lateral Bracing System on Stringer Diaphragms

No Direct Influence

C3 Stiffener Configuration

Choices to be made:

- Type
- Position
- Moment Regions
- Intersection of Stiffeners

C4

Influence of Stiffener Configuration on Floorbeam Configuration

- If transverse stiffeners are used as floorbeam connection plates, stiffeners are not permitted to have any web gaps.
- If longitudinal stiffener intersects floorbeam connection plate, a case which should be avoided, then the longitudinal stiffener should not be interupted.

C5

Influence of Stiffener Configuration on Diaphragm System

- If transverse stiffeners are used as diaphragm connection plates, stiffeners are not permitted to have any web gaps.

- If longitudinal stiffener intersects diaphragm connection plate, a case which should be avoided, then the longitudinal stiffener should not be interrupted.

C6

Influence of Stiffener Configuration on Stringer Configuration

No Direct Influence

C7

Influence of Stiffener Configuration on Stringer Diaphragms

No Direct Influence

D4 Floorbeam Configuration

Choices to be made:

- Existence and Type
- Position (In Relation to Girder Level)
- Connection To Girder
    - Connection Plates
    - Connection Angles
    - Continuous, Passing Through Girder
- Deck Action
- Floorbeam Brackets Used
- Cantilever Brackets Used
    - Tie Plates Used
    - Welds Used on Tie Plates
    - Cantilever Bracket Connection To Girder

D5

Influence of Floorbeam Configuration on Diaphragm System

- It is assumed that a diaphragm system will only be used in a multi-girder bridge without floorbeams, therefore, there should be no influence.

D6

Influence of Floorbeam Configuration on Stringer Configuration

- If there are no floorbeams, there will be no stringers.

- If floorbeam level is below the level of the girder, the stringers should rest on top of the floorbeam, and possibly be braced. This allows both the girders and stringers to act at the same level, where they both can be composite with the deck and share the deck load.

- If floorbeam level is at the level of the girders, the stringers could be either at or below the level of the main girders. There are problems associated with both conditions. If the stringers are above the level of the girders they may have to be braced, and if they are at the level of the girders and floorbeams, there may be problems at the stringer to floorbeam connection.

D7

Influence of Floorbeam Configuration on Stringer Diaphragms

- If there are no floorbeams, there will be no stringer diaphragms.
- Floorbeam level influences the level of the stringers, which in turn, influences stringer diaphragms.

E5 Diaphragm System

Choices to be made:

- Existence and Type
- Connection To Girder
- Deck Action

E6

Influence of Diaphragm System on Stringer Configuration

No Direct Influence

E7

Influence of Diaphragm System on Stringer Diaphragms

No Direct Influence

F6 Stringer Configuration

Choices to be made:

- Existence and Type
- Position
- Connection To Floorbeam
- Deck Action

F7

Influence of Stringer Configuration on Stringer Diaphragms

- If there are no stringers, then there will be no stringer diaphragms.
- If stringers are at the level of the floorbeams, then there is no need to use stringer diaphragms, unless they are necessary for construction purposes.

G7 Stringer Diaphragms

Choices to be made:

- Existence and Type
- Position
- Connection To Stringers

Appendix C

FDC Validation Tests

Appendix C
FDC Validation Testing

Validation Testing:

The purpose of the validation testing is to test a representative sampling of possible variables and combinations and paths. The following tables summarize the categories of validation cases used for FDC. The tables are organized by purpose, expectation, what is held constant (given), what is varied, and how it is varied. Two levels of testing are distinguished [Chen 88]:

1. Module Unit Testing (MUT) - A compilation and logic error detection process for individual modules within FDC.

2. Module Integration Testing (MIT) - The functionality of the integration of modules within the FDC system.

Validation Test Case Categories
Table C.1 Description of Bridge Macro-Parameters

Purpose	Expect	Given	Vary		Level
			What	How	
Is the "nature" of the bridge described by the bridge objects ?	yes, according to design morphology selected	General bridge characteristics	Macro-parameters	By selecting different combinations of macro-parameters	MUT
		2 girder bridge			
		Multi-girder bridge			
Does bridge description support recommended modifications to macro-parameters ?	yes	Different combinations of general bridge characteristics	Macro-parameters	By selecting different combinations of macro-parameters	MIT
		2 girder bridge			
		Multi-girder bridge			

Validation Test Case Categories
Table C.2 Recommended Modifications to Macro-Parameters

Purpose	Expect	Given	Vary		Level
			What	How	
Are suitable (more fatigue resistant) macro-parameters recommended in commentary ?	yes, according to domain expert	Bridge macro-parameters and commentary provided by system	Commentary provided by system	By selecting different combinations of macro-parameters	MUT
		2 girder bridge			
		Multi-girder bridge			
Is commentary provided by system on effect of macro-parameters on possible details supported by detail design stage of operation ?	yes	Bridge macro-parameters and commentary provided by system	Commentary provided by system on influence of macro-parameters on design of individual details	By selecting different combinations of macro-parameters	MIT
		2 girder bridge			
		Multi-girder bridge			

Validation Test Case Categories

Table C.3 Description of Individual Bridge Details

Purpose	Expect	Given	Vary		Level
			What	How	
Is the "nature" of each individual detail described by the physical objects ?	yes	Input on specific details on the bridge	Types and combinations of details specified	By selecting different combinations of members and connections	MUT
		2 girder bridge			
		Multi-girder bridge			
Does individual detail description support commentary and recommendations provided by the system ?	yes	Input on specific details on the bridge	Types and combinations of details specified	By selecting different combinations of members and connections	MIT
		2 girder bridge			
		Multi-girder bridge			

Validation Test Case Categories
Table C.4 Determination of Interplay of Details

Purpose	Expect	Given	Vary		Level
			What	How	
Determine validity and integrity of design dependency network	yes	Details that exist on the structure and network of design dependencies	Ramifications to be incurred at other details	Vary input for specific details	MUT
Determine if commentary and recommendations are consistent with design dependency network	yes, for the hierarchy of details selected	Details that exist on the structure and network of design dependencies	Ramifications to be incurred at other details	Vary input for specific details	MIT

Validation Test Case Categories
Table C.5 Commentary and Recommendations For Details

Purpose	Expect	Given	Vary		Level
			What	How	
To determine if appropriate commentary and recommendations are provided by FDC	yes	Description of specific detail	Topology and connectivity of specific detail	Vary user input	MUT
Does the commentary and recommendations reflect the commentary provided at the macro-parameter level ?	yes	Description of specific detail and macro-parameter commentary	Macro-parameters	Vary user input	MIT
Is the commentary and recommendations consistent with the design dependency network ?	yes	Design dependency network and topology and connectivity of specific detail	Topology and connectivity of other bridge details	Vary user input	MIT

Appendix D

FDC Field Study

Canoe Creek Bridge

Canoe Creek Bridge

FDC Evaluation

The following screen captures show a portion of the FDC evaluation conducted on the Canoe Creek Bridge.

Introductory Screens:

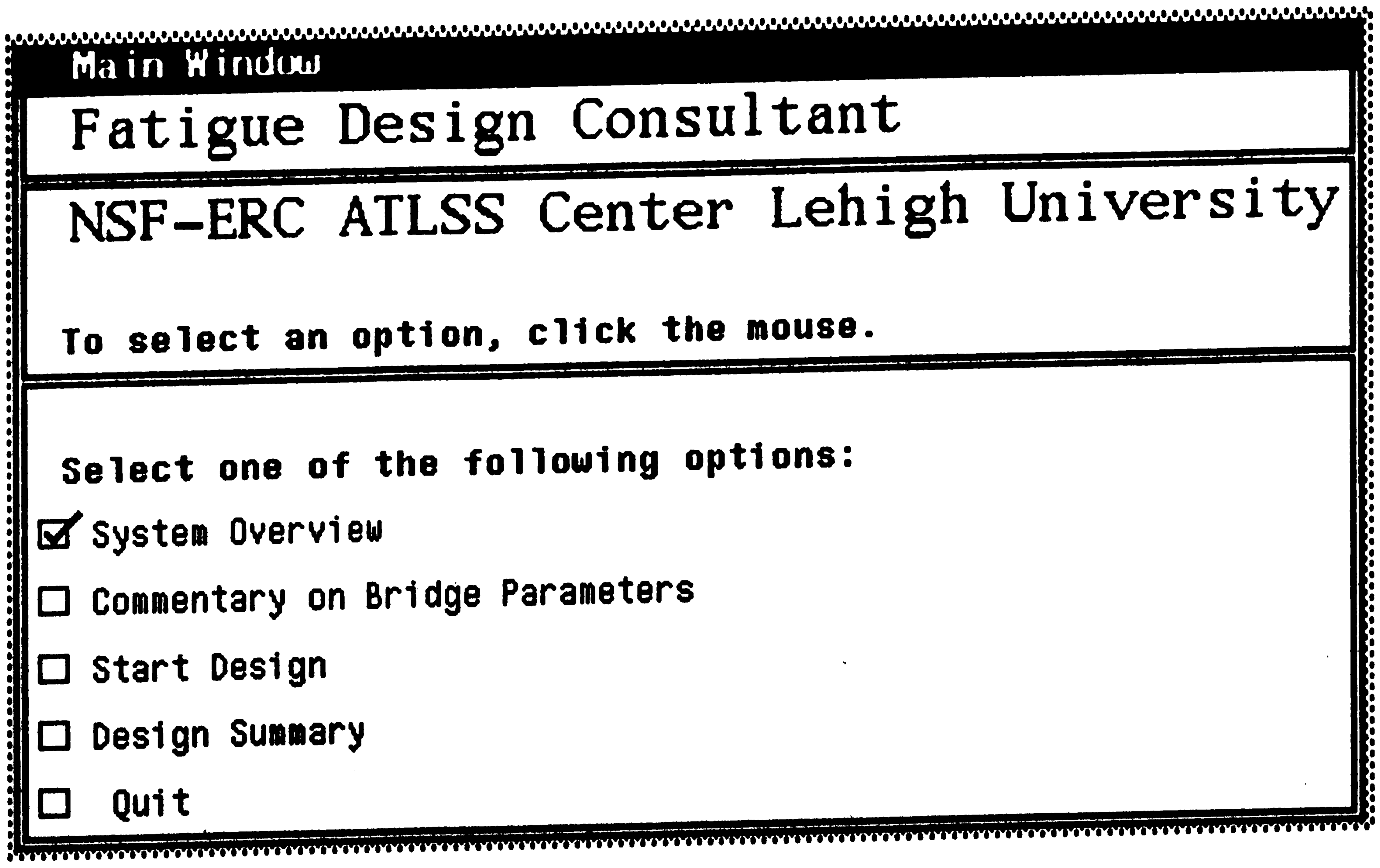
WELCOME TO THE FATIGUE DESIGN CONSULTANT

(Copyright)

NSF-ERC ATLSS Center - Lehigh University

(Advanced Technology for Large Structural Systems)

Knowledge-Based Systems Research Group



Fatigue Design Consultant

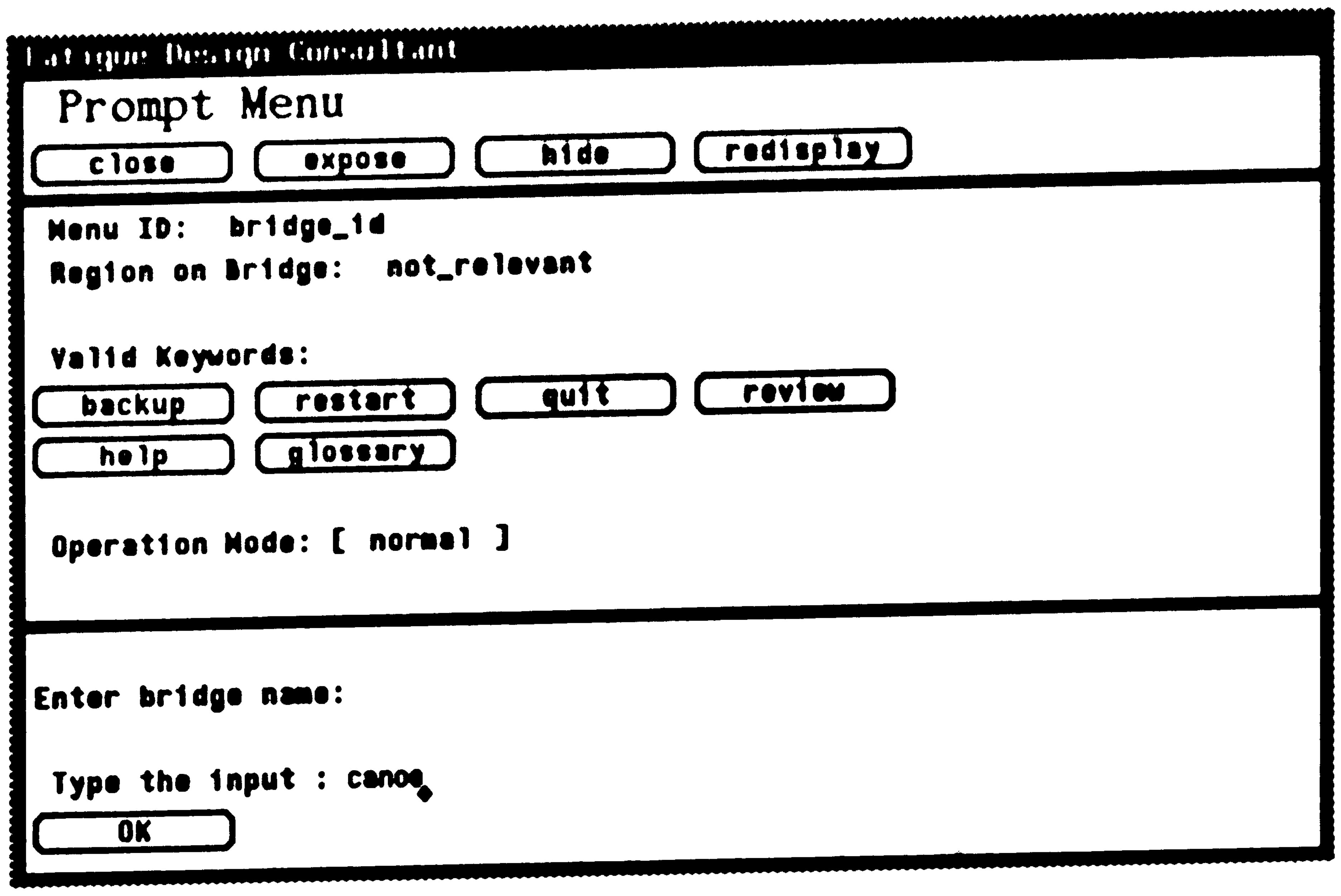
NSF-ERC ATLSS Center Lehigh University

To select an option, click the mouse.

Select one of the following options:

☑ System Overview
☐ Commentary on Bridge Parameters
☐ Start Design
☐ Design Summary
☐ Quit

The first stage of the FDC evaluation is a commentary on the bridge's macro-parameters. The user is asked a number of questions on these parameters, and FDC evaluates how these parameters will influence the fatigue performance of the structure. A number of these initial questions are shown below.



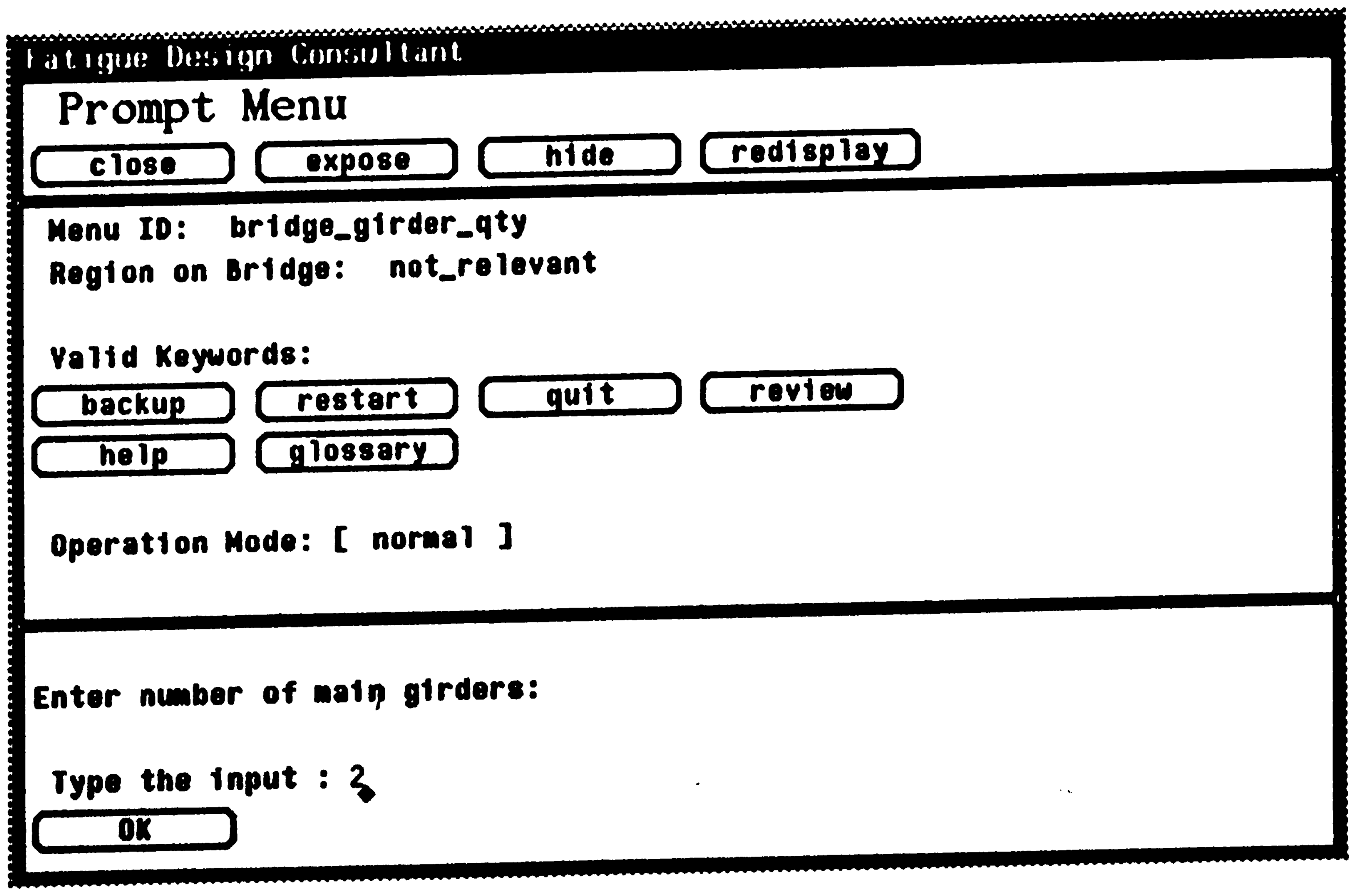
Menu ID: bridge_id
Region on Bridge: not_relevant

Valid Keywords:

Operation Mode: [normal]

Enter bridge name:

Type the input : canoe



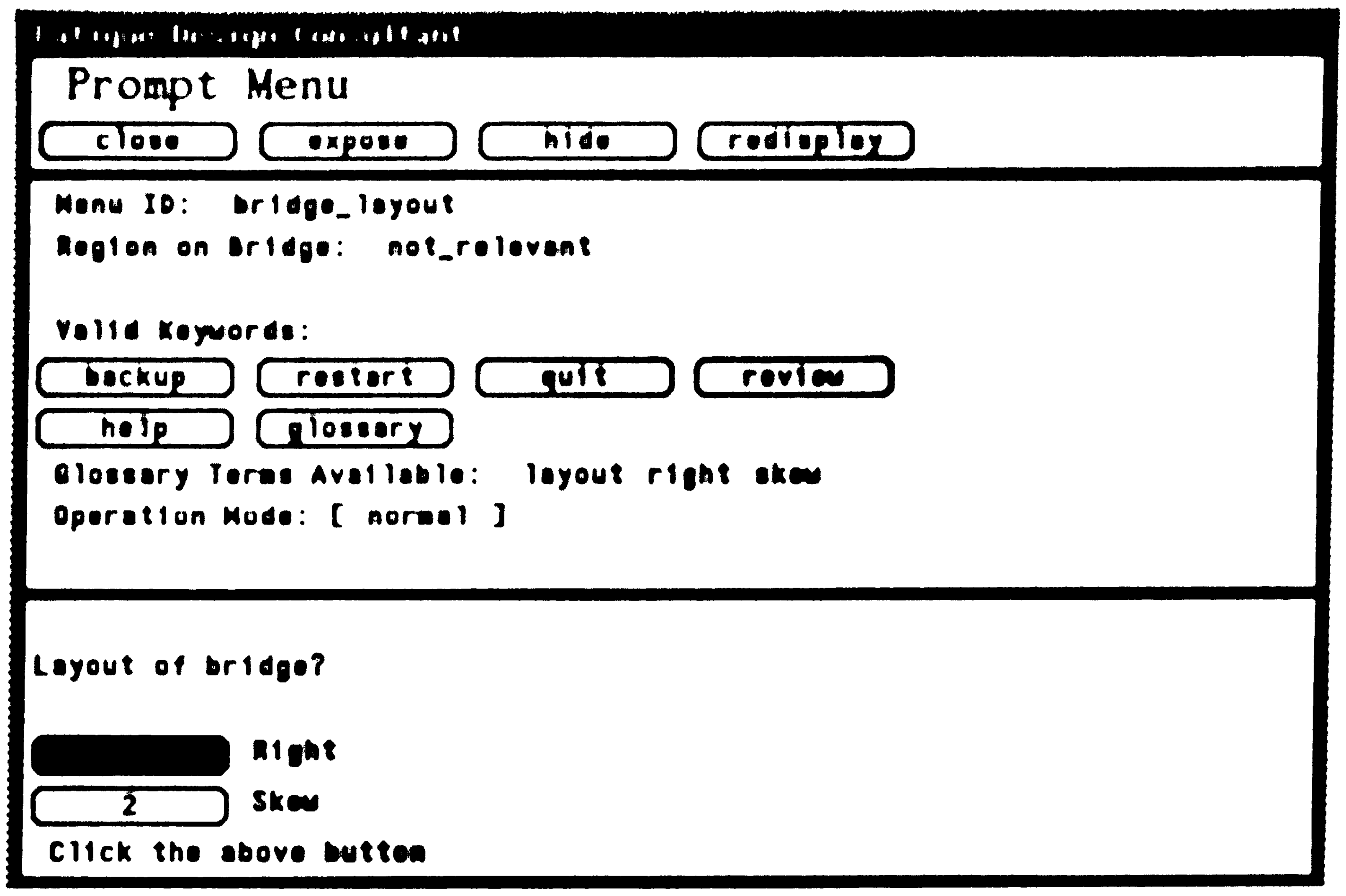
Menu ID: bridge_girder_qty
Region on Bridge: not_relevant

Valid Keywords:

Operation Mode: [normal]

Enter number of main girders:

Type the input : 2



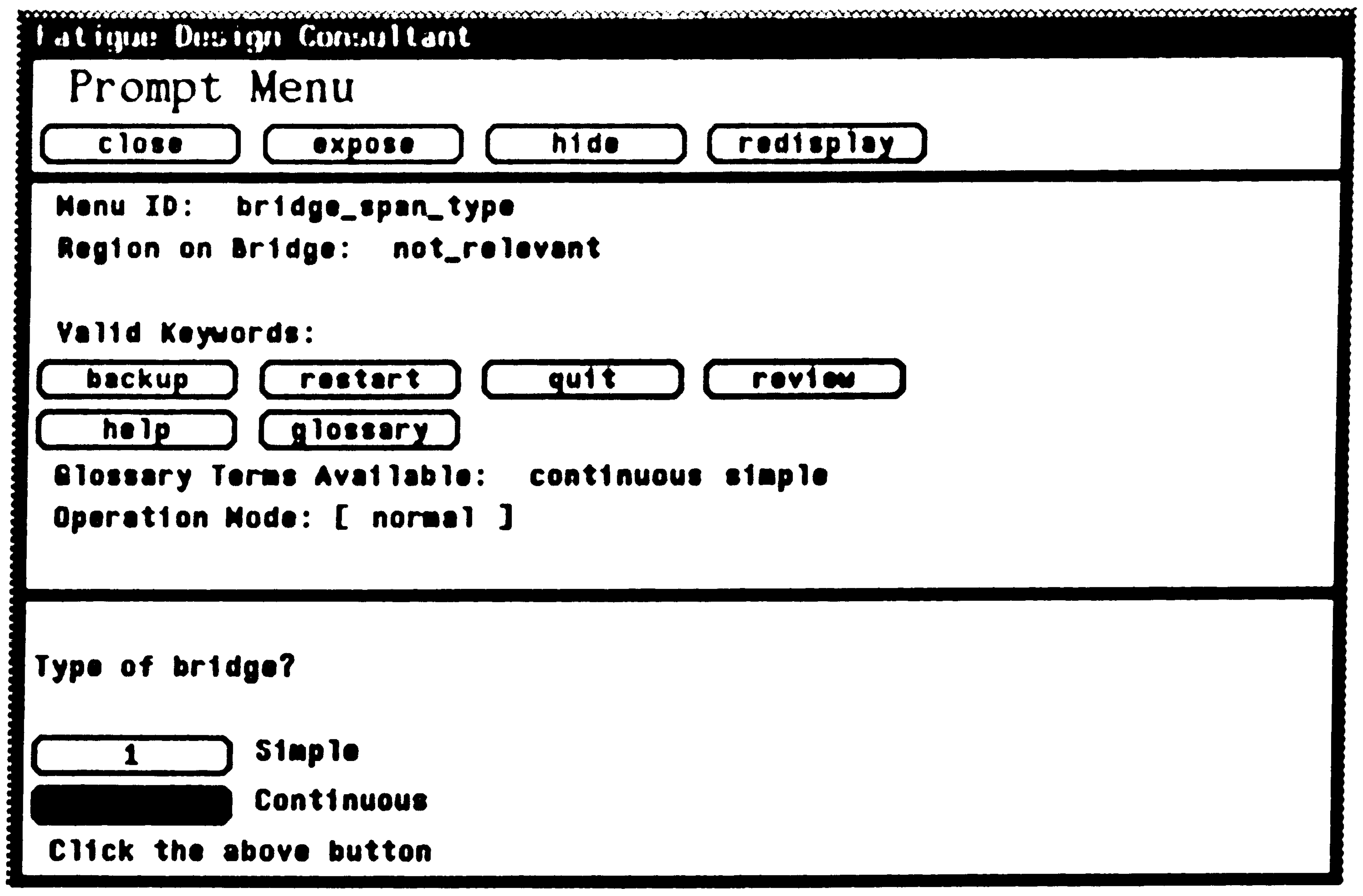
Menu ID: bridge_layout
Region on Bridge: not_relevant

Glossary Terms Available: layout right skew
Operation Mode: [normal]

Layout of bridge?

● Right
2 Skew

Click the above button



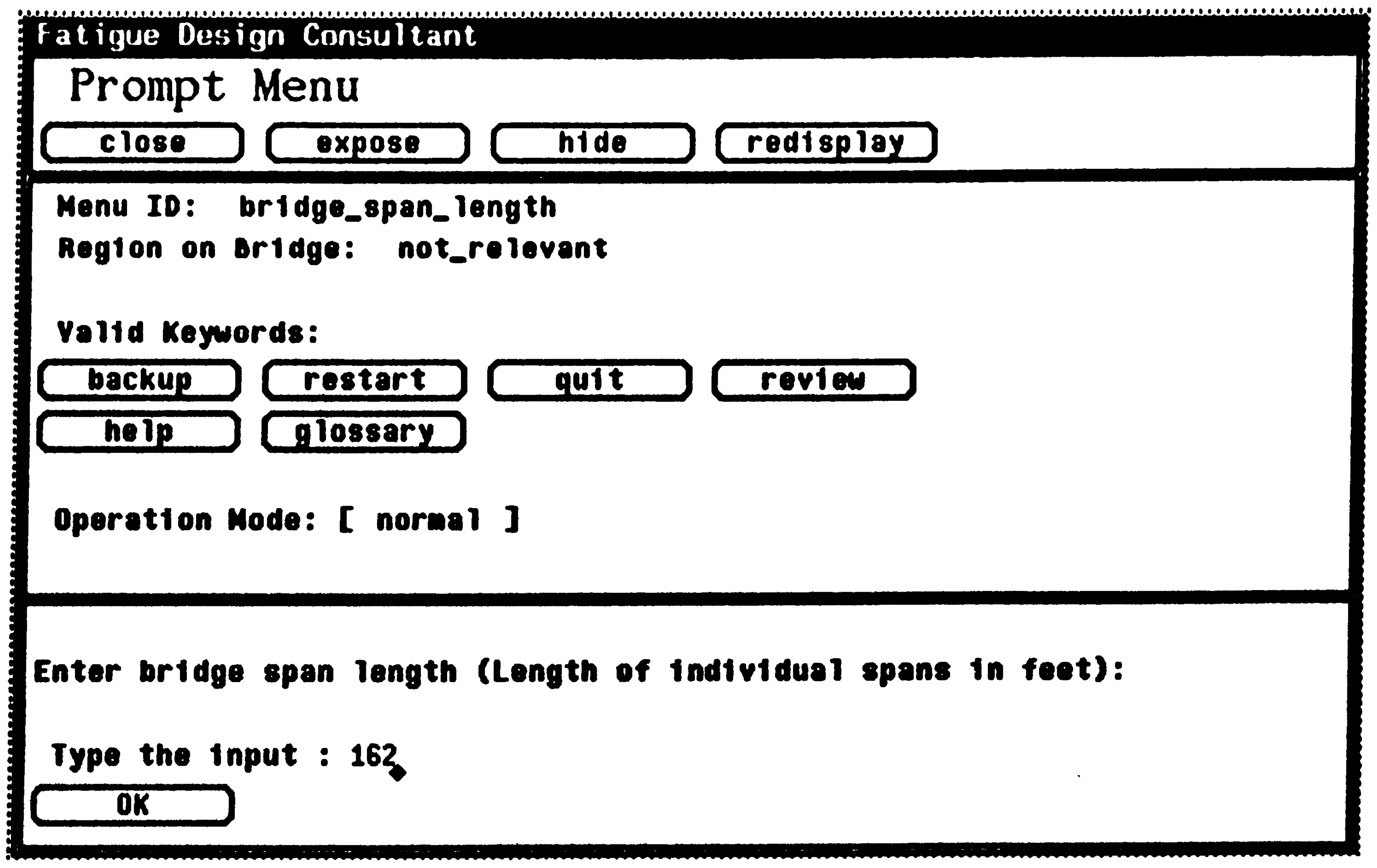
Menu ID: bridge_span_type
Region on Bridge: not_relevant

Glossary Terms Available: continuous simple
Operation Mode: [normal]

Type of bridge?

1 Simple
● Continuous

Click the above button



Menu ID: bridge_span_length
Region on Bridge: not_relevant

Operation Mode: [normal]

Enter bridge span length (Length of individual spans in feet):

Type the input : 162

After all of the questions have been answered by the user, FDC provides its commentary on the macro-parameters. The commentary supplied by FDC for the Canoe Creek Bridge, and taken directly from an FDC output file, can be seen below.

```
*** COMMENTS ON BRIDGE MACRO-PARAMETERS ***

        COMMENT ON BRIDGE LAYOUT
 Right bridges such as these are less susceptible to
certain types of fatigue problems than their skew
counterparts. In addition, any fatigue problems which
do exist will be less severe than those in skew bridges
because skew bridges are subjected to differential
girder deflection which magnifies the effects of
distortion-induced fatigue.



        COMMENT ON GIRDER QUANTITY
 Two girder bridges are considered fracture
critical, and therefore, redundancy may be
a problem.  It has been shown that lateral
bracing systems greatly improve the strength
and redundancy of these type of structures.

In addition, it will be assumed that with a
two-girder bridge, a floorbeam/stringer system
```

is to be used.

COMMENT ON BRIDGE SPAN LENGTH

Bridge span length is one of the factors which help determine if a bottom lateral bracing system is required on the bridge. However, since there are only two main girders on this structure, it is advisable to use a bottom lateral system regardless of other factors. This system will help increase the redundancy of the structure, which is critical in two girder bridges.

COMMENT ON BRIDGE SPAN TYPE

Continuous bridges such as this often have more fatigue problems than their simple counterparts because higher stresses often develop at intermediate supports, a situation which can increase the severity of fatigue problems.

COMMENT ON DECK COMPOSITE ACTION

By not making the girder composite with the deck, the lateral strength and stability of the top girder flange is reduced. Therefore a top-lateral bracing system may be considered. Also, there may be problems due to

differential deflection of the main girders, or differential rotation between the main girders and the deck. Problems may be encountered at lateral gusset plates and cantilever brackets.

COMMENT ON NUMBER OF POS. X-SECTIONS

Since there is only one type of positive cross-section, any fatigue problems will be consistent throughout the positive moment region.

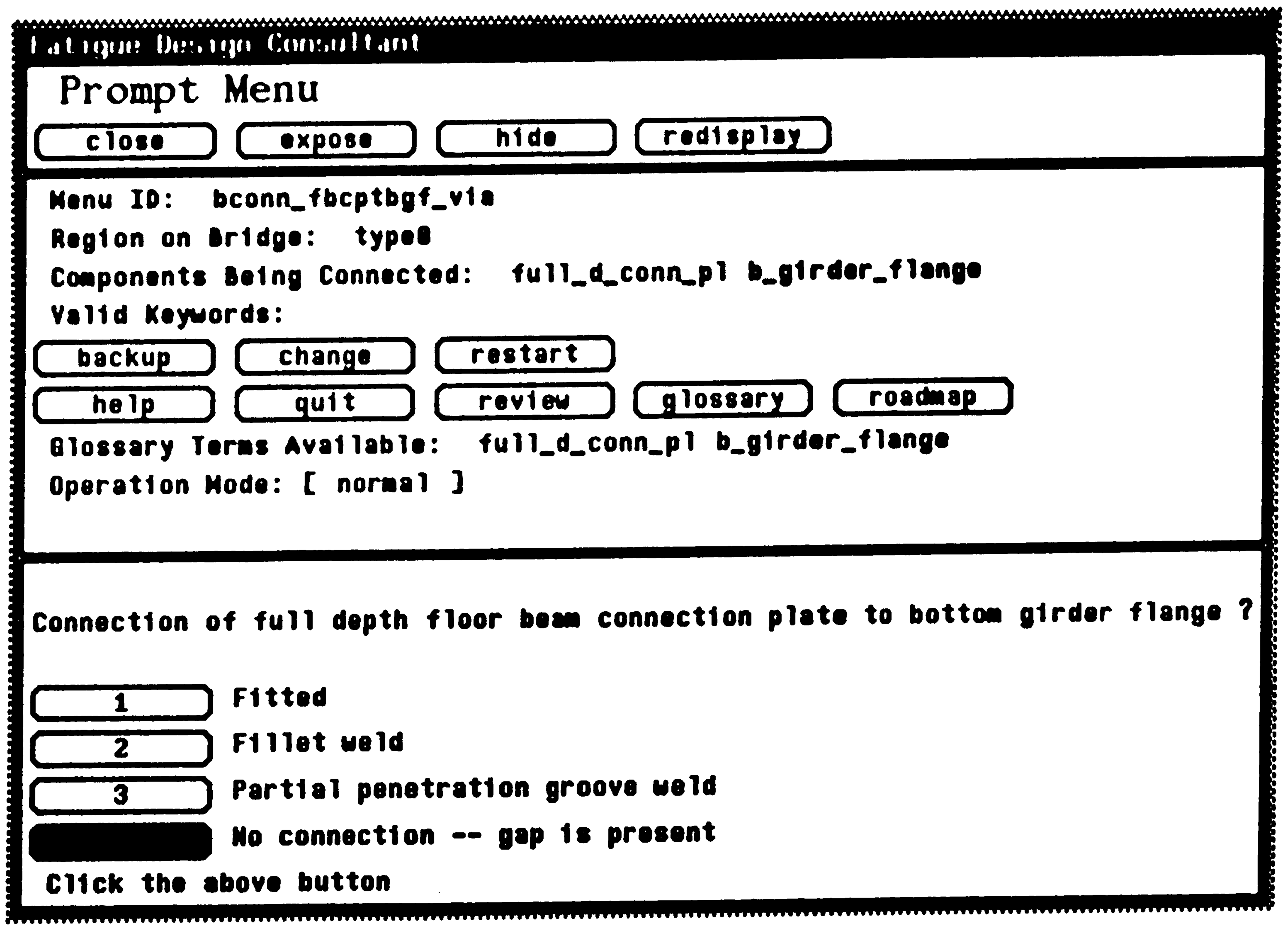
COMMENT ON ADTT/DESIGN LIFE

The projected ADTT (Average Daily Truck Traffic) and design life of the structure place this bridge in a category of bridges with expected lifetime fatigue stress cycles greater than 2,000,000. This category is reserved for major roadways by AASHTO, and represents the most severe fatigue condition.

After FDC has provided commentary on the bridge macro-parameters, the user can begin the preliminary qualitative design of different details on the structure. An evaluation of each selection is then made by FDC. The following portion of the Canoe Creek session shows FDC's evaluation of the four details known to have experienced fatigue cracking on the existing structure.

Detail #1 - Vertical Gap At Bottom End Of Floorbeam Conn. Plates

The designer's selection which resulted in this detail, was the use of a gap at the floorbeam connection plate to bottom girder flange connection in the positive moment region. This selection is depicted below, and the commentary and recommendation of FDC, taken directly from an FDC output file, is provided on the following page.



```
Menu ID:  bconn_fbcptbgf_v1a
Region on Bridge:  type8
Components Being Connected:  full_d_conn_pl b_girder_flange
Valid Keywords:
Glossary Terms Available:  full_d_conn_pl b_girder_flange
Operation Mode: [ normal ]

Connection of full depth floor beam connection plate to bottom girder flange ?

1  Fitted
2  Fillet weld
3  Partial penetration groove weld
●  No connection -- gap is present
Click the above button
```

FDC - Positive Aspects:
connection plate to bottom girder flange connection

NO COMMENT AT THIS TIME

FDC - Negative Aspects:
connection plate to bottom girder flange connection

CONNECTION VIA GAP

1) For this moment region, the gap is at the tension flange.

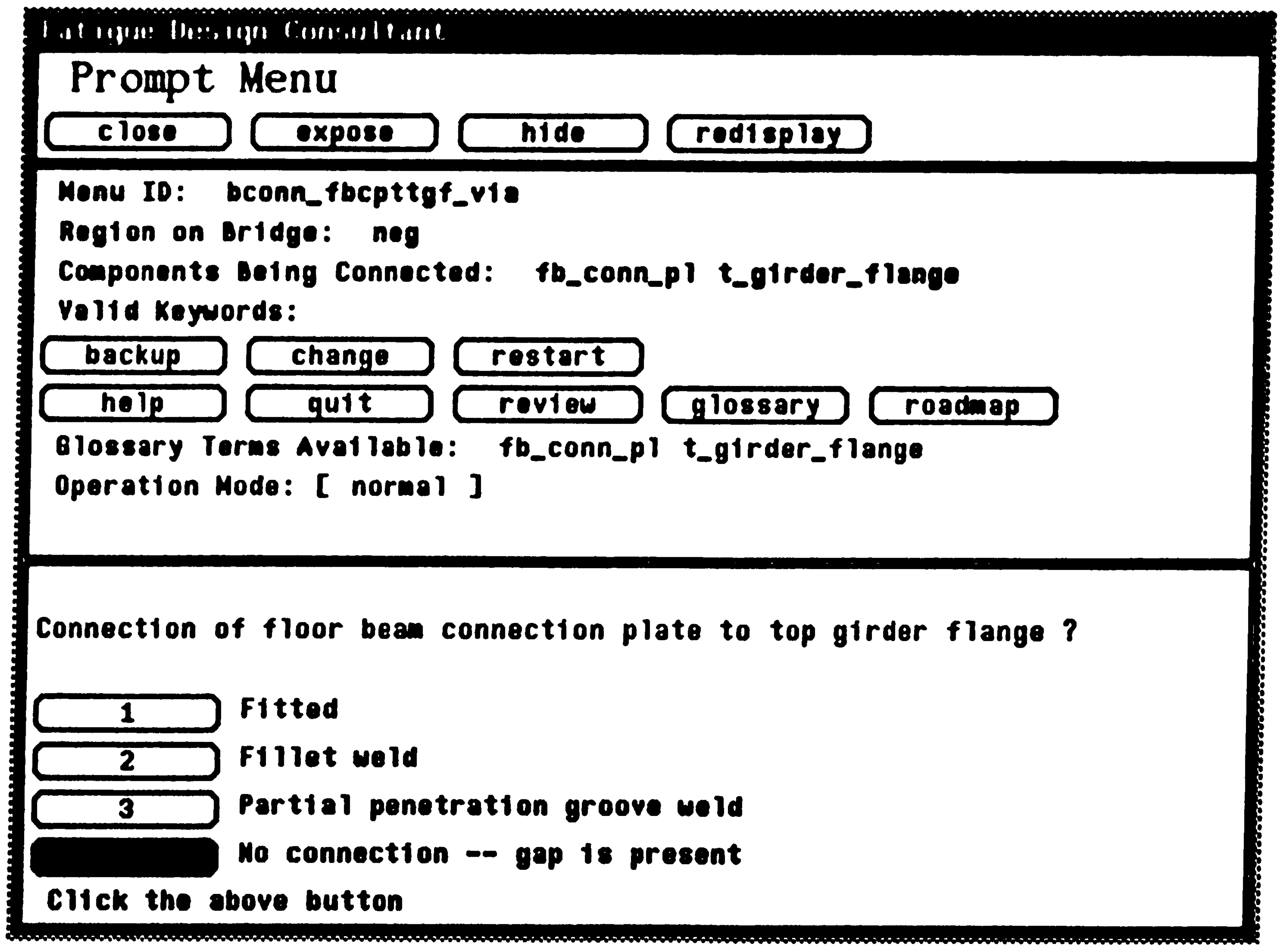
2) Extremely high stresses are developed in the gap region due to distortion, often caused by movement of the transverse members connected to the plate.

FDC - Recommendation:
RECOMMENDATION ON GAP

It is never advisable to have a gap at the end of a plate connecting a transverse member to the main girder. A positive connection should be made. Bolting is the best alternative, however, fillet welding is better than leaving a gap.

Detail #2 - Vertical Gap At The Top End Of Floorbeam Connection Plates In The Negative Moment Region

The designer's selection which resulted in this detail, was the use of a gap at the floorbeam connection plate to top girder flange connection, in the negative moment region. This selection is depicted below, and the commentary and recommendation of FDC, taken directly from an FDC output file, is provided on the following page.



```
Menu ID:  bconn_fbcpttgf_via
Region on Bridge:  neg
Components Being Connected:  fb_conn_pl t_girder_flange
Valid Keywords:
Glossary Terms Available:  fb_conn_pl t_girder_flange
Operation Mode: [ normal ]

Connection of floor beam connection plate to top girder flange ?

[ 1 ] Fitted
[ 2 ] Fillet weld
[ 3 ] Partial penetration groove weld
●     No connection -- gap is present
Click the above button
```

FDC - Positive Aspects:
connection plate to top girder flange connection

NO COMMENT AT THIS TIME

FDC - Negative Aspects:
connection plate to top girder flange connection

CONNECTION VIA GAP

1) For this moment region, the gap is at the tension flange.

2) Extremely high stresses are developed in the gap region due to distortion, often caused by movement of the transverse members connected to the plate.

FDC - Recommendation:
RECOMMENDATION ON GAP

It is never advisable to have a gap at the end of a plate connecting a transverse member to the main girder. A positive connection should be made. Bolting is the best alternative, however, fillet welding is better than leaving a gap.

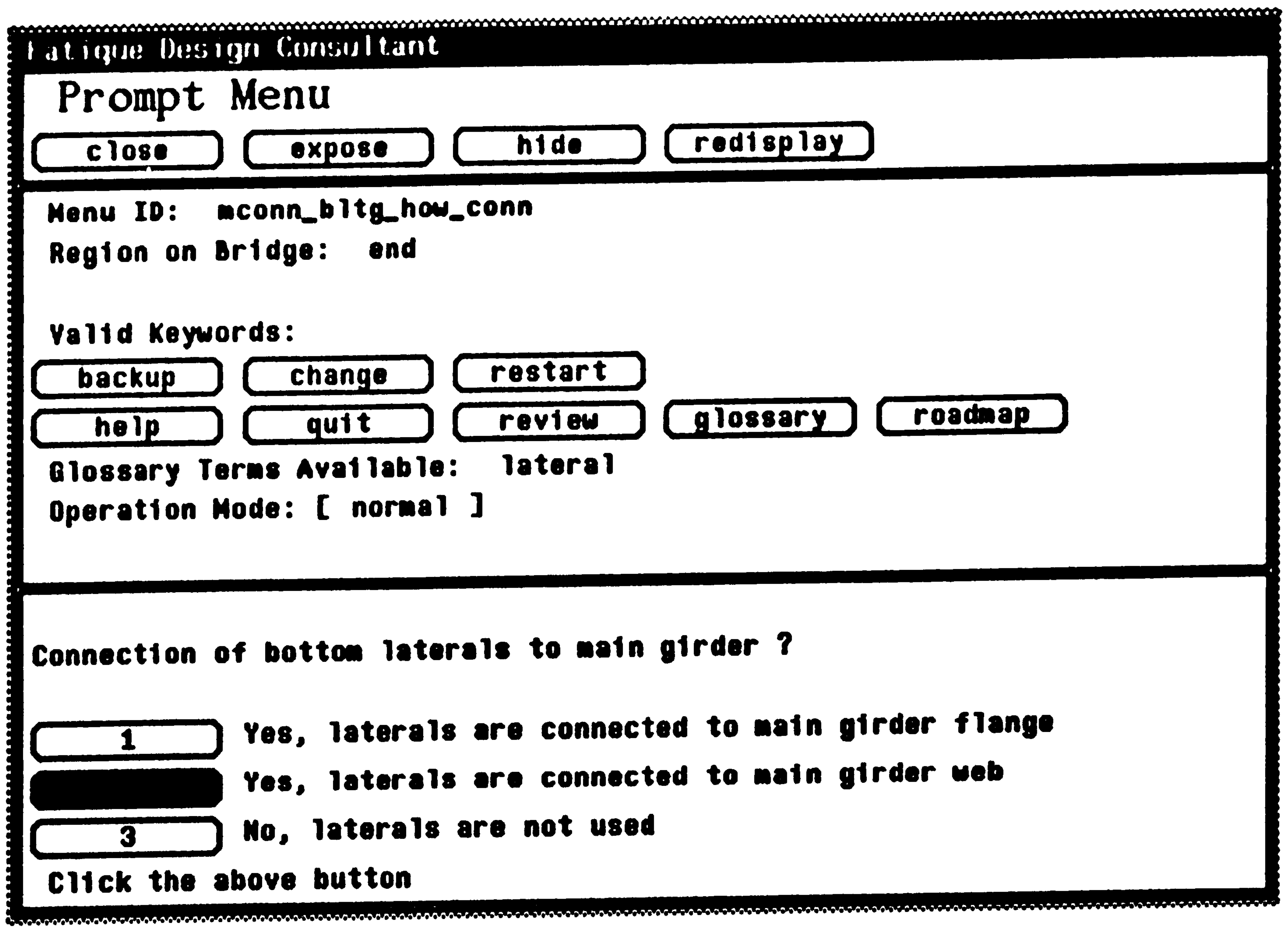
Detail #3 - Ends Of The Lateral Bracing Connection Plate Tabs Welded To The Girder Web

Detail #4 - Horizontal Gap Between The Lateral Bracing Connection Plates And Floorbeam Connection Plates

Both of these details, which experienced fatigue cracking on the Canoe Creek Bridge, are associated with the topology of the lateral bracing system. Therefore, the user's selections which describe this topology will be shown below, each followed by the commentary and recommendations, taken directly from an FDC output file.

Parameter #1 - The Use Of A Lateral Bracing System:

Designer's Selection - Lateral System Used; Connected To Main Girder Web



Menu ID: mconn_bltg_how_conn
Region on Bridge: end

Valid Keywords:
Glossary Terms Available: lateral
Operation Mode: [normal]

Connection of bottom laterals to main girder ?

1 Yes, laterals are connected to main girder flange
● Yes, laterals are connected to main girder web
3 No, laterals are not used
Click the above button

FDC - Positive Aspects:
LATERALS TO GIRDER WEB

Web lateral gusset plates are easy to attach to. Connection can be made with bolting.

FDC - Negative Aspects:
LATERALS TO GIRDER WEB

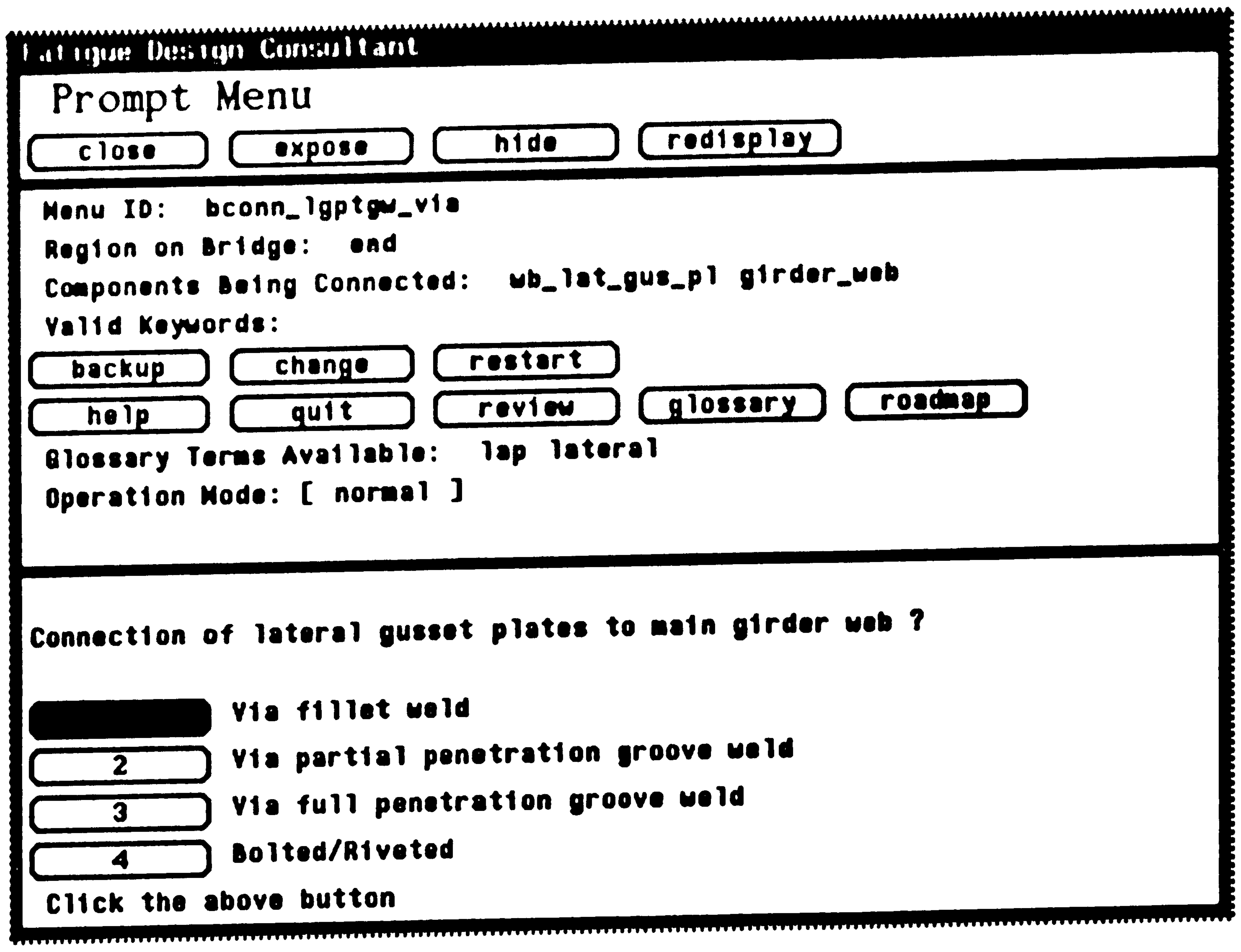
There are a number of fatigue problems associated with the use of web lateral gusset plates, including the possibility of intersecting welds, and fatigue due to vibration of the laterals.

FDC - Recommendation:
RECOMMENDATION FOR LATERALS

If possible, the use of a bottom lateral bracing system should be avoided. Section 10.20.2 of AASHTO gives the requirements for use of this type of system. If a lateral system is required, it is better to connect this system to the girder flange. If connected to the web, fatigue problems may occur, and it is more likely the system will intersect other components.

Parameter #2 - Connection Of Web Lateral Gusset Plate To Main Girder Web:

Designer's Selection - Web Gusset Plate (Tabs) Fillet Welded To Girder Web



Menu ID: bconn_lgptgw_via
Region on Bridge: end
Components Being Connected: wb_lat_gus_pl girder_web
Valid Keywords:
Glossary Terms Available: lap lateral
Operation Mode: [normal]

Connection of lateral gusset plates to main girder web ?

● Via fillet weld
2 Via partial penetration groove weld
3 Via full penetration groove weld
4 Bolted/Riveted

Click the above button

FDC - Positive Aspects:
WEB GUSSET CONNECTION VIA FILLET

This type of weld is easy to perform. In addition, the stress range in the web will be lower than at the flange.

FDC - Negative Aspects:
WEB GUSSET CONNECTION VIA FILLET

1)The fatigue category of this detail is E or E prime.

2)There is the possibility of intersecting welds, if this gusset plate intersects a stiffener or conn. plate.

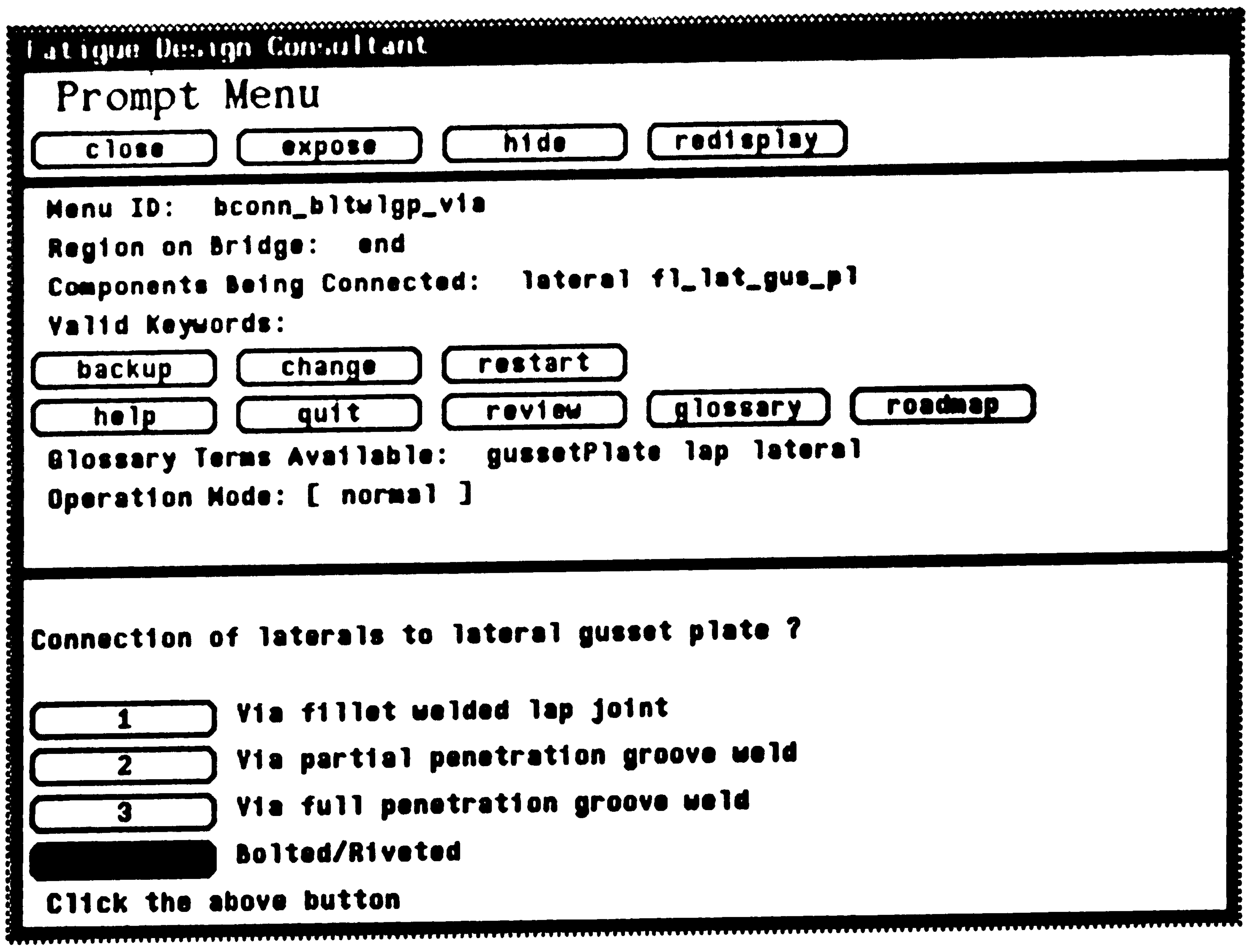
3)There may be fatigue problems due to vibration of the laterals, if they are not properly connected to the gusset plate.

FDC - Recommendation:
RECOMMENDATTION ON WEB GUSSET FILLET

If possible, the lateral system should be connected to the girder flange. If this cannot be done, the gusset plate should be bolted to the girder web. If fillet welding is to be used, it is important to avoid intersecting components and perhaps provide a radiused transition at the end of the weld.

Parameter #3 - Connection Of Laterals To Lateral Gusset Plate

Designer's Selection - Laterals Bolted To Web Lateral Gusset Plate



Menu ID: bconn_bltwlgp_via
Region on Bridge: end
Components Being Connected: lateral fl_lat_gus_pl
Valid Keywords:
Glossary Terms Available: gussetPlate lap lateral
Operation Mode: [normal]

Connection of laterals to lateral gusset plate ?

1 Via fillet welded lap joint
2 Via partial penetration groove weld
3 Via full penetration groove weld
● Bolted/Riveted
Click the above button

FDC - Positive Aspects:
LATERALS TO GUSSET PLATE
VIA BOLTING

Bolting at this connection can easily be performed, and is best for fatigue performance.

FDC - Negative Aspects:
LATERALS TO GUSSET PLATE
VIA BOLTING

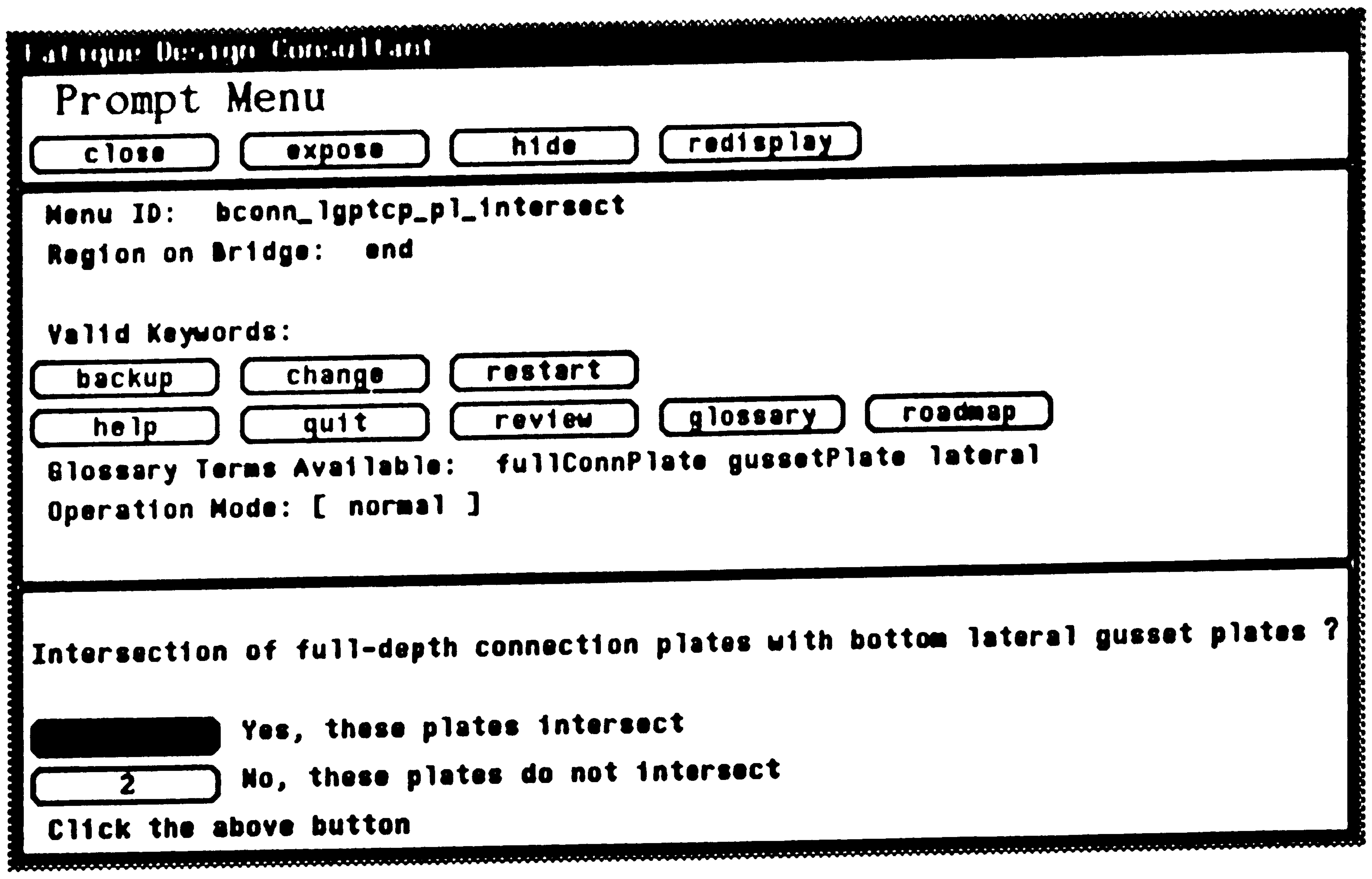
The connection of the laterals to the gusset plate is susceptible to fatigue from vibration of the laterals.

FDC - Recommendation:
RECOMMENDATION ON CONNECTION
OF LATERALS TO GUSSET

The best connection is made by bolting. However, for any type of connection, proper distance from the ends of the laterals to the point of connection of the gusset to girder should be maintained. This, along with decreasing the flexibility of the laterals will help avoid vibration problems.

Parameter #4 - Intersection Of **Lateral** Gusset Plates And **Floorbeam Conn. Plates**

Designer's Selection - Lateral Gusset Plate And Floorbeam Conn. **Plates Intersect**



Menu ID: bconn_lgptcp_pl_intersect

Region on Bridge: end

Valid Keywords:

Glossary Terms Available: fullConnPlate gussetPlate lateral

Operation Mode: [normal]

Intersection of full-depth connection plates with bottom lateral gusset plates ?

● Yes, these plates intersect

2 No, these plates do not intersect

Click the above button

FDC - Positive Aspects:
NO COMMENT AT THIS TIME

FDC - Negative Aspects:
INTERSECTION BETWEEN GUSSET AND CONNECTION PLATES

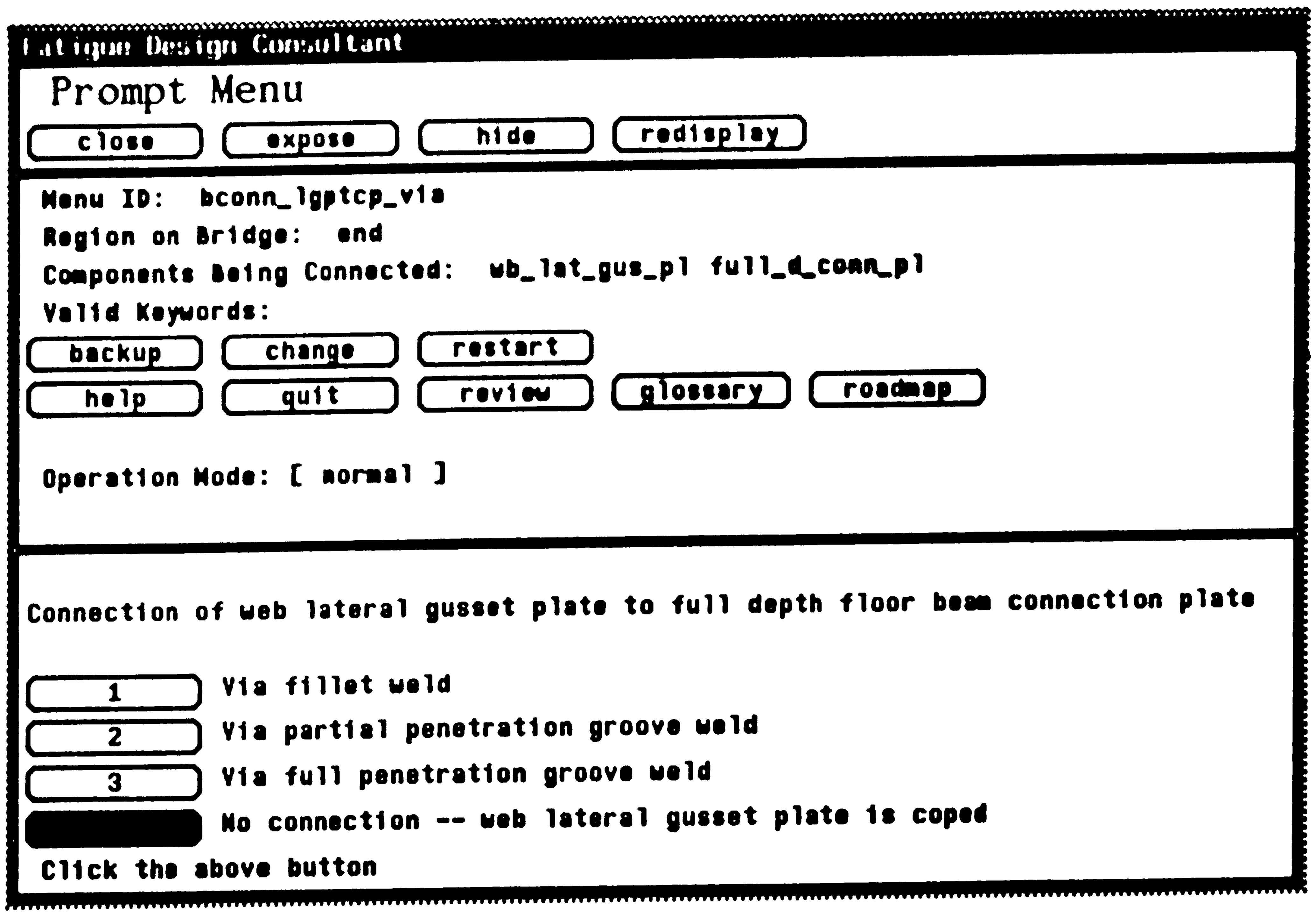
There are a great many fatigue problems that have occurred at the intersection of lateral gusset plates and the connection plates of transverse members.

FDC - Recommendation:
RECOMMENDATION ON INTERSECTION OF GUSSET AND CONNECTION PLATES

It is highly recommended that the intersection of these two components be avoided. Modifying the manner of connecting the laterals to the girder is suggested. If these components must intersect, it is recommended that a positive attachment between the gusset and connection plates be made.

Parameter #5 - Connection of Lateral Gusset Plate To Floorbeam Connection Plate

Designer's Selection - Lateral Gusset Plate Is Coped At Intersection



Menu ID: bconn_lgptcp_via
Region on Bridge: end
Components Being Connected: wb_lat_gus_pl full_d_conn_pl
Valid Keywords:

Operation Mode: [normal]

Connection of web lateral gusset plate to full depth floor beam connection plate

1 Via fillet weld
2 Via partial penetration groove weld
3 Via full penetration groove weld
● No connection -- web lateral gusset plate is coped
Click the above button

FDC - Positive Aspects:
GUSSET COPED AT INTERSECTION
WITH TRANSVERSE PLATES

This coping of the lateral gusset plate will avoid the use of intersecting welds.

FDC - Negative Aspects:
GUSSET COPED AT INTERSECTION
WITH TRANSVERSE PLATES

If the gap between the coped gusset and the transverse plate is not large enough, very large web bending stresses can be introduced into the gap region and cracking may occur.

FDC - Recommendation:
RECOMMENDATION ON CONNECTION
OF GUSSET AND CONN. PLATES

It is recommended that a single gusset be used. This gusset should be coped to avoid intersecting the conn.plate to girder connection, but should be welded to the conn.plate away from the girder web. The cope gap should be at least four to six times the thickness of the girder web, but not less than two inches. Also, if possible the transverse member should be connected to the gusset plate.

Appendix E

FDC Field Study

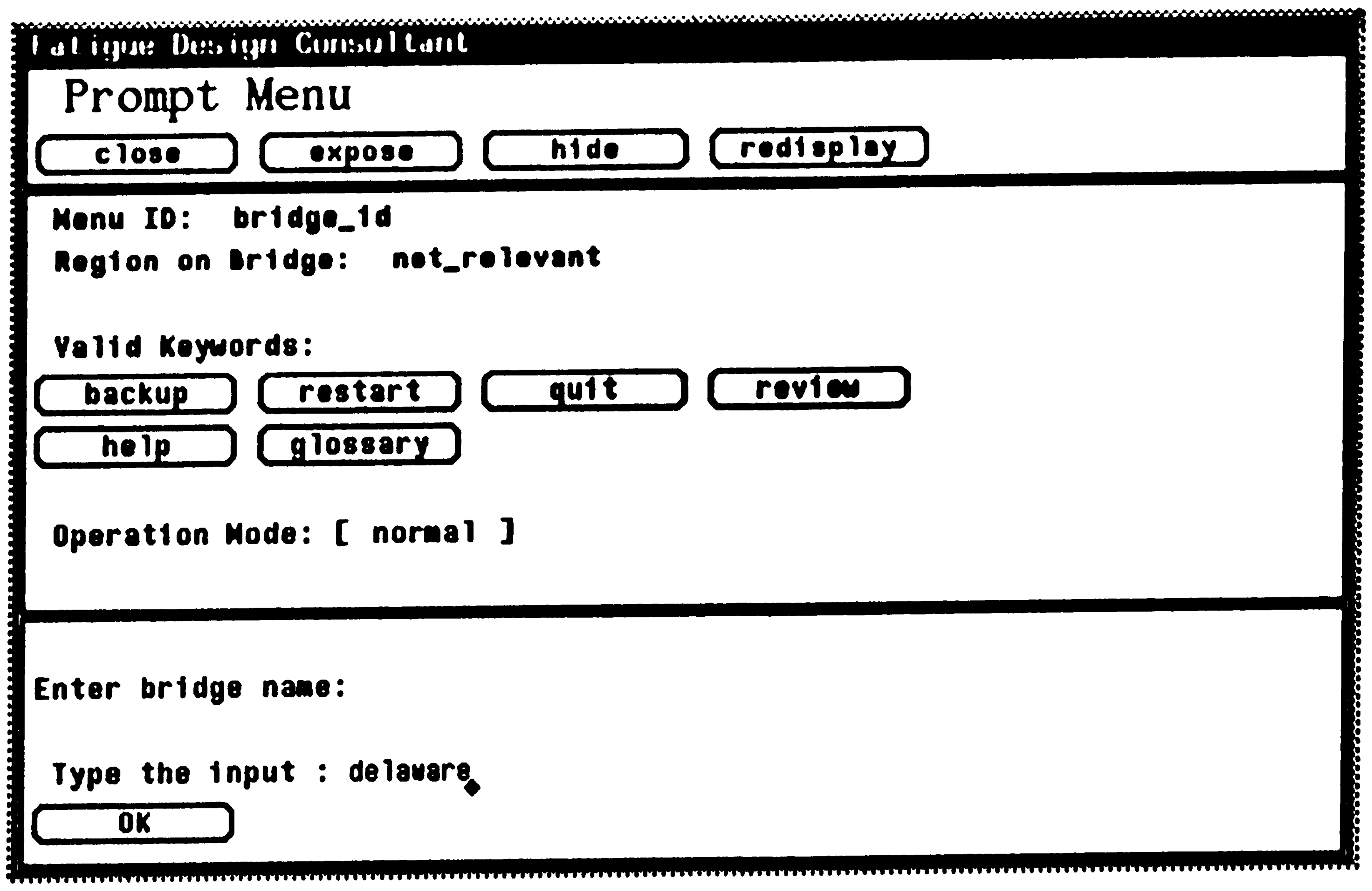
I-78 Delaware River Bridge

I-78 Delaware River Bridge

FDC Evaluation

The following screen captures show a portion of the FDC evaluation conducted on the I-78 Delaware River Bridge.

The first stage of the FDC evaluation is a commentary on the bridge's macro-parameters. The user is asked a number of questions on these parameters, and FDC evaluates how these parameters will influence the fatigue performance of the structure. A number of these initial questions are shown below.



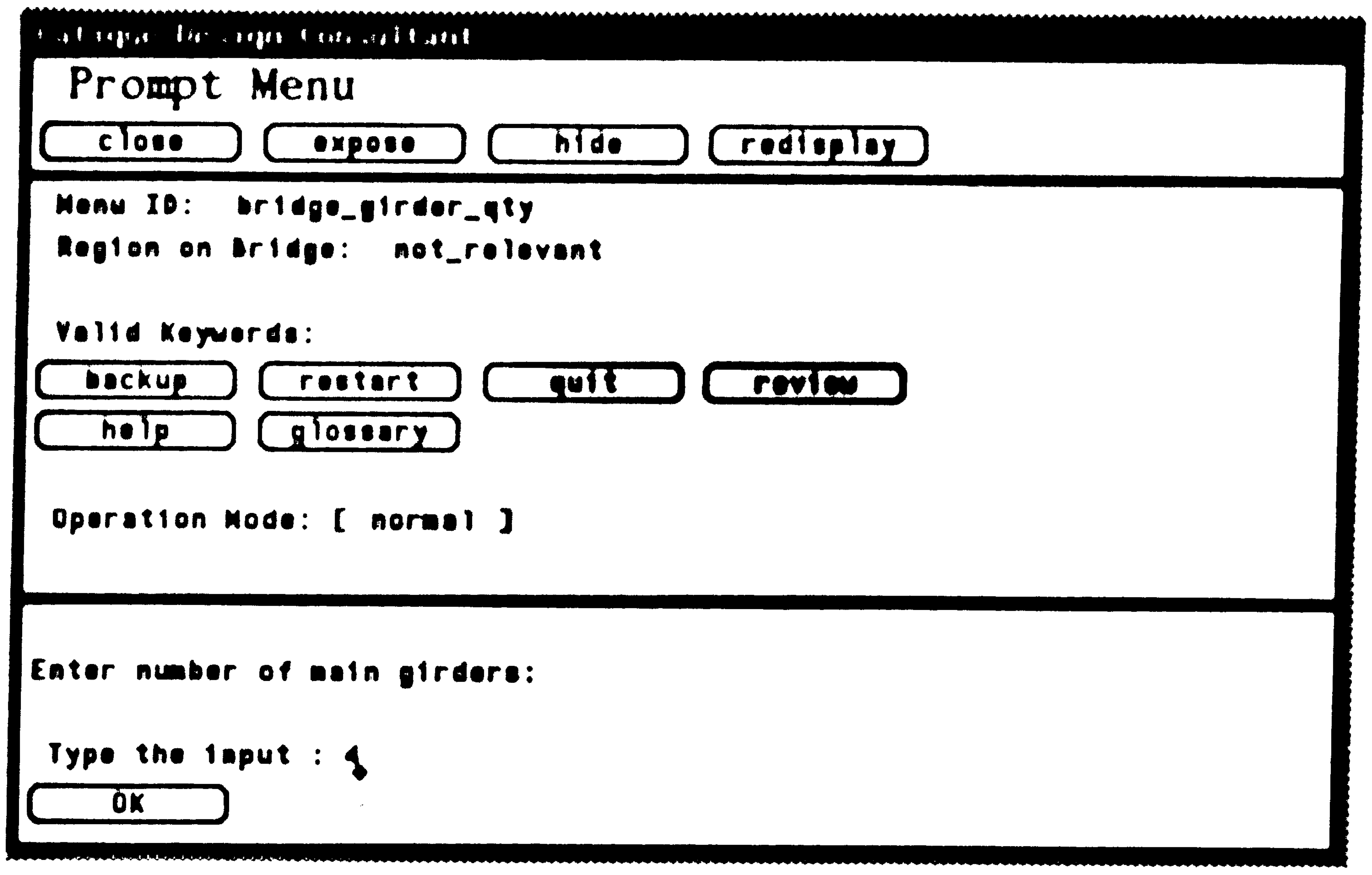
Menu ID: bridge_id
Region on Bridge: not_relevant

Valid Keywords:

Operation Mode: [normal]

Enter bridge name:

Type the input : delaware



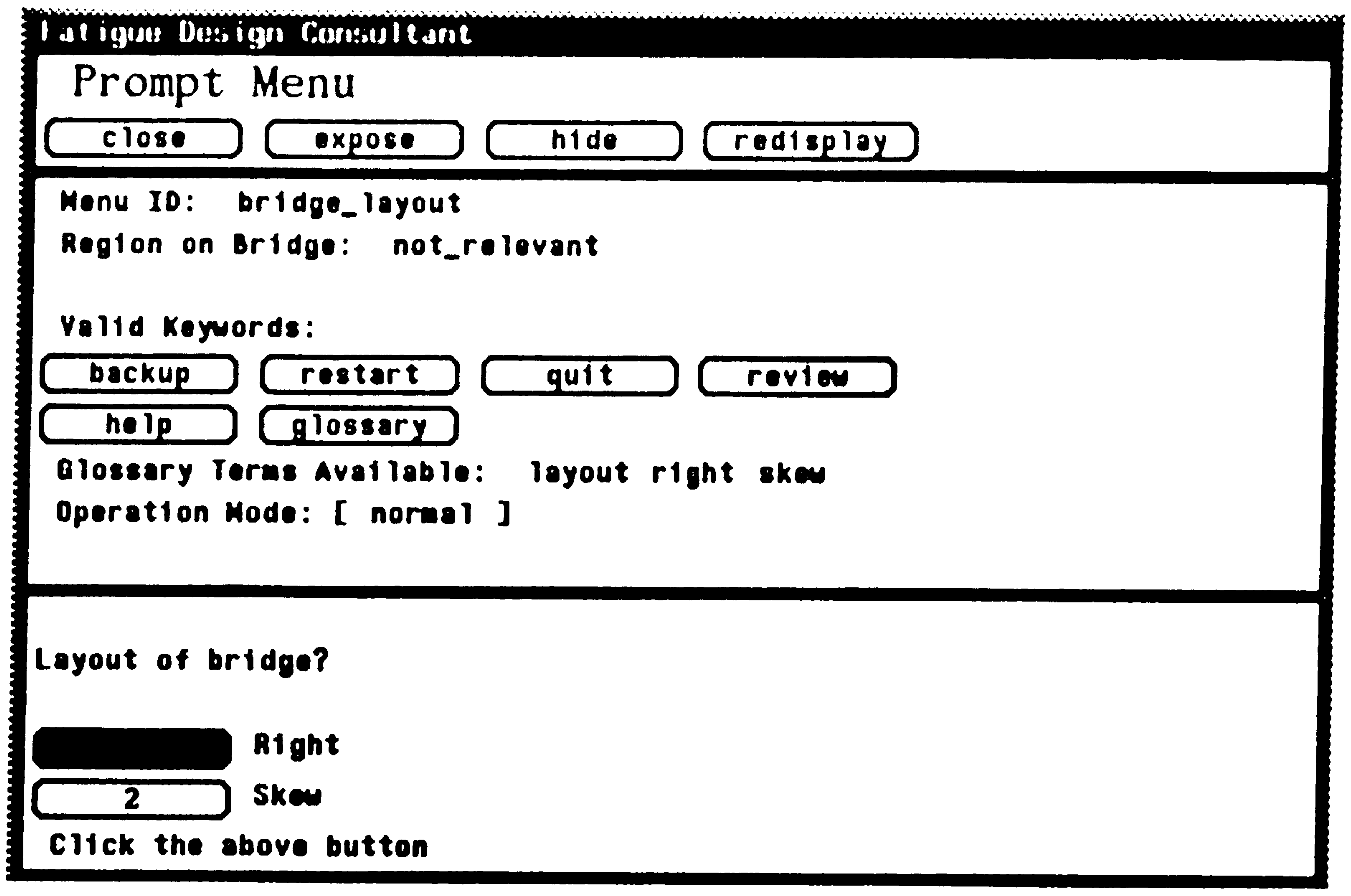
Menu ID: bridge_girder_qty
Region on Bridge: not_relevant

Valid Keywords:

Operation Mode: [normal]

Enter number of main girders:

Type the input : 4



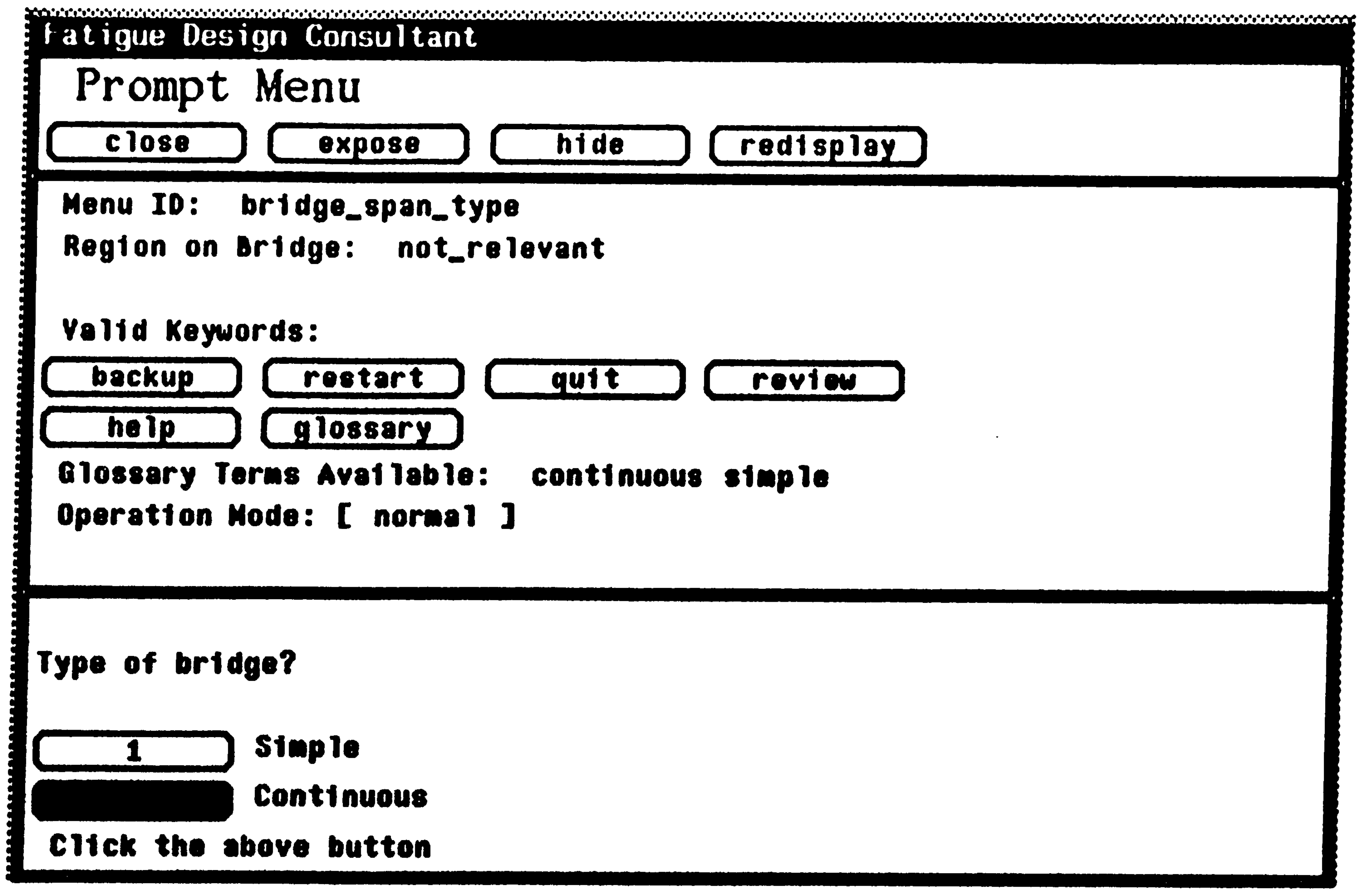
Menu ID: bridge_layout
Region on Bridge: not_relevant

Valid Keywords:

Glossary Terms Available: layout right skew
Operation Mode: [normal]

Layout of bridge?

Right
2 Skew
Click the above button



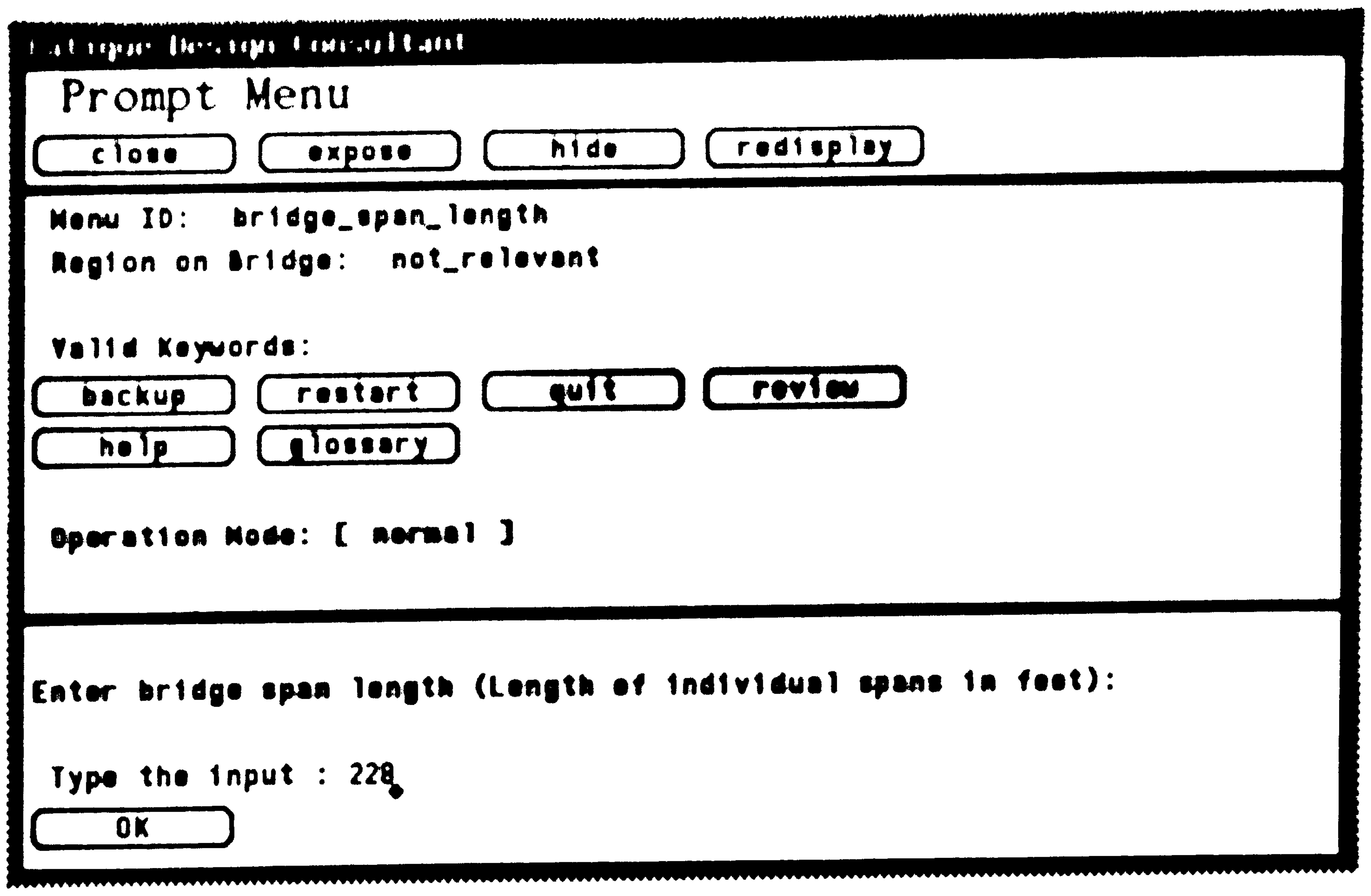
Menu ID: bridge_span_type
Region on Bridge: not_relevant

Valid Keywords:

Glossary Terms Available: continuous simple
Operation Mode: [normal]

Type of bridge?

1 Simple
Continuous
Click the above button



Menu ID: bridge_span_length
Region on Bridge: not_relevant

Operation Mode: [normal]

Enter bridge span length (Length of individual spans in feet):

Type the input : 228

After all of the questions have been answered by the user, FDC provides its commentary on the macro-parameters. The commentary supplied by FDC for the I-78 Delaware River Bridge, taken directly from an FDC output file, can be seen below.

*** COMMENTS ON BRIDGE MACRO-PARAMETERS ***

COMMENT ON BRIDGE LAYOUT

Right bridges such as these are less susceptible to certain types of fatigue problems than their skew counterparts. In addition, any fatigue problems which do exist will be less severe than those in skew bridges because skew bridges are subjected to differential girder deflection which magnifies the effects of distortion-induced fatigue.

COMMENT ON GIRDER QUANTITY

These type of bridges, may or may not have floorbeam/stringer systems. In any case, the redundancy of structures with three or four girders is better than that of two girder bridges.

COMMENT ON BRIDGE SPAN LENGTH

Since there are more than two main girders, it may or may not be necessary to use a lateral bracing system on this structure. Span length, along with a number of other parameters, that will be selected at a later stage in the design process, will determine whether or not a bottom lateral system will be required. Generally, the shorter the the span length, the less likely a bottom lateral system will be needed.

COMMENT ON BRIDGE SPAN TYPE

Continuous bridges such as this often have more fatigue problems than their simple counterparts because higher stresses often develop at intermediate supports, a situation which can increase the severity of fatigue problems.

COMMENT ON DECK COMPOSITE ACTION

Composite girder/deck action serves to increase the lateral strength and stability of the top girder flange. By doing so, the need for a top-lateral bracing system is eliminated. Also, composite action will help minimize the differential deflection between girders, and differential rotation between the girders and deck and help eliminate fatigue problems due to these causes.

COMMENT ON NUMBER OF POS. X-SECTIONS

Since there is only one type of positive cross-section, any fatigue problems will be consistent throughout the positive moment region.

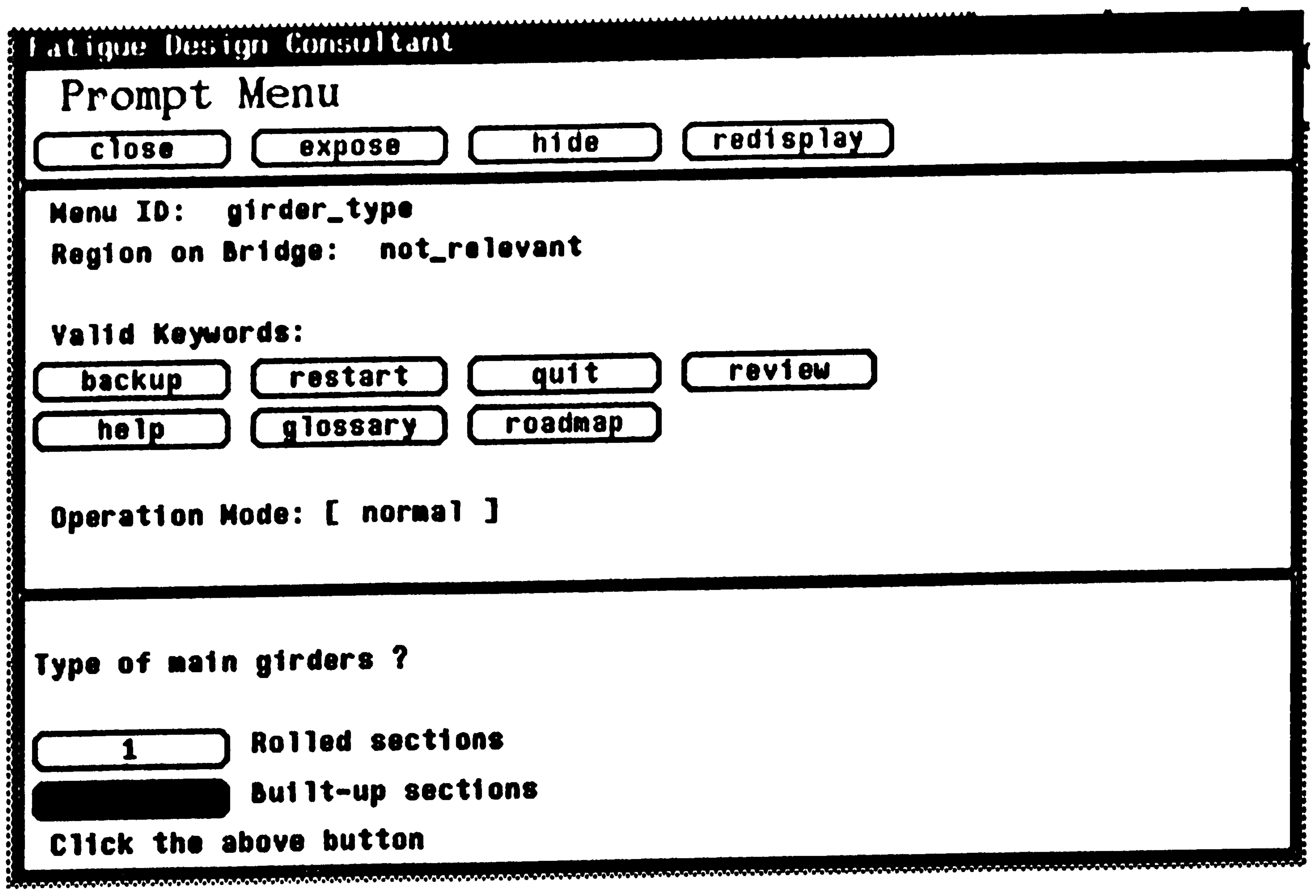
COMMENT ON ADTT/DESIGN LIFE

The projected ADTT (Average Daily Truck Traffic) and design life of the structure place this bridge in a category of bridges with expected lifetime fatigue stress cycles greater than 2,000,000. This category is reserved for major roadways by AASHTO, and represents the most severe fatigue condition.

After FDC has provided commentary on the bridge macro-parameters, the user can begin the preliminary qualitative design of different details on the structure, receiving an evaluation of each selection he makes. The following example shows a typical evaluation made by FDC for the Delaware River Bridge.

Detail - Connection Of Main Girder Flange To Web

The designer's selections which resulted in this detail, were the use of built-up main girder sections with continuous fillet welds to connect the girder flange and web. These two selections are depicted below, each followed by the commentary and recommendation of FDC, taken directly from an FDC output file.



Menu ID: girder_type
Region on Bridge: not_relevant

Valid Keywords:

Operation Mode: [normal]

Type of main girders ?

1 Rolled sections
Built-up sections
Click the above button

FDC - Positive Aspects:

GIRDER TYPE - BUILT-UP MAIN GIRDERS

1) Built-Up girders are available for larger sections.

2) It is assumed that cover plates will not be used on built-up girders, and therefore, fatigue problems associated with the termination of longitudinal welds on cover plates will be avoided.

FDC - Negative Aspects:

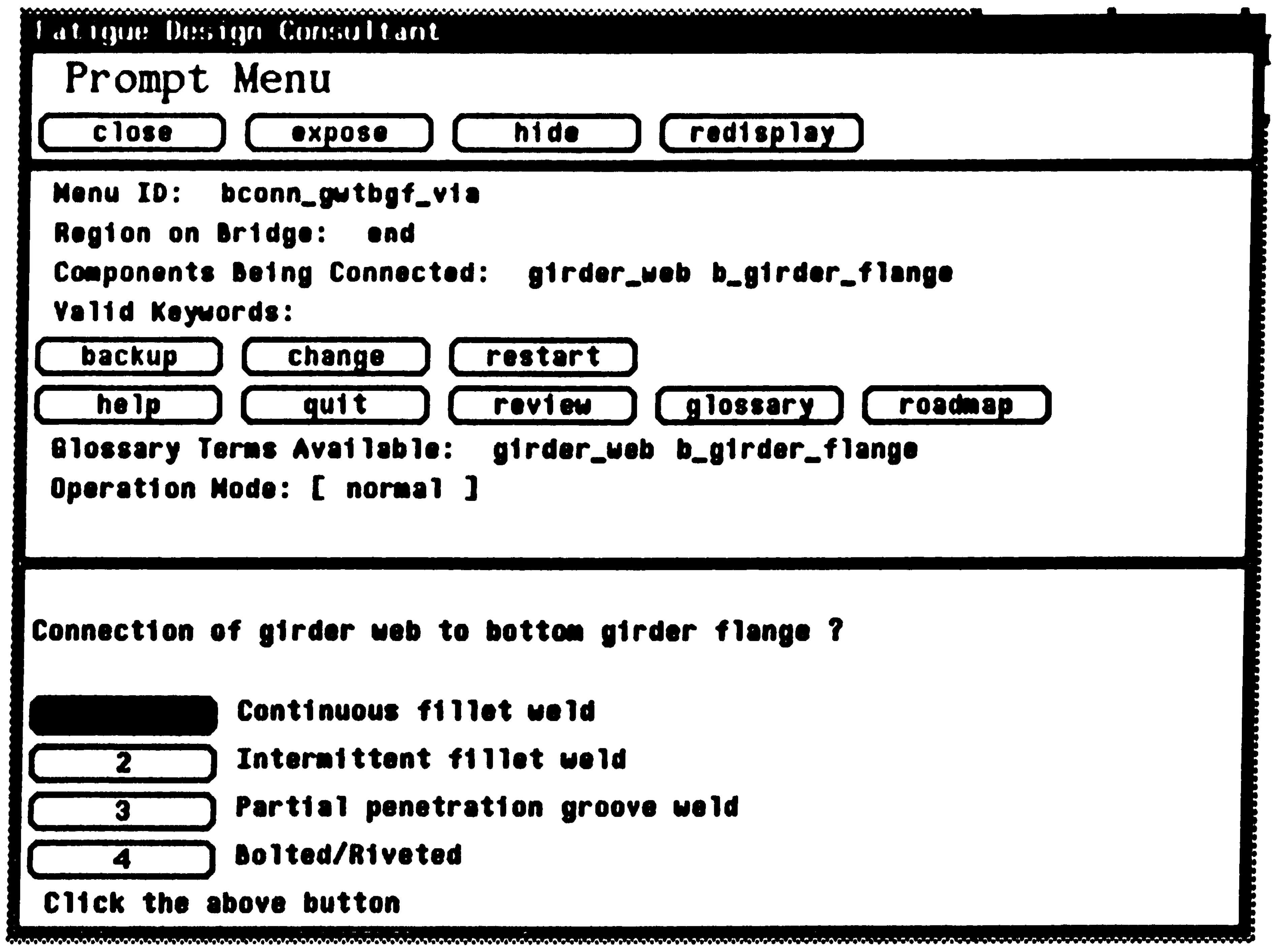
GIRDER TYPE - BUILT-UP MAIN GIRDERS

1) Built-up main girders often need stiffeners, both longitudinal and transverse, therefore there are many potential problems that may be encountered. The need for these stiffeners is governed by the dimensions of the main girders, and stipulated in bridge codes.

2)The connection of the web to flange may be susceptible to fatigue, specifically if the connection will be made by welding.

FDC - Recommendation:
RECOMMENDATION FOR GIRDER TYPE

Built-up members are the only alternative when rolled members of the necessary size cannot be found. While both types of main girders have their own unique types of fatigue problems, the cost of the main members is greatly increased if built-up members must be fabricated. Therefore, if possible, use rolled main girders.



Menu ID: bconn_gwtbgf_via
Region on Bridge: end
Components Being Connected: girder_web b_girder_flange
Valid Keywords:
Glossary Terms Available: girder_web b_girder_flange
Operation Mode: [normal]

Connection of girder web to bottom girder flange ?

● Continuous fillet weld
2 Intermittent fillet weld
3 Partial penetration groove weld
4 Bolted/Riveted
Click the above button

FDC - Positive Aspects:
girder web to bottom girder flange connection

CONNECTION VIA FILLET OR
INTERMITTENT FILLET WELD

These types of welding procedures are inexpensive to perform both in the shop and in the field.

FDC - Negative Aspects:

girder web to bottom girder flange connection

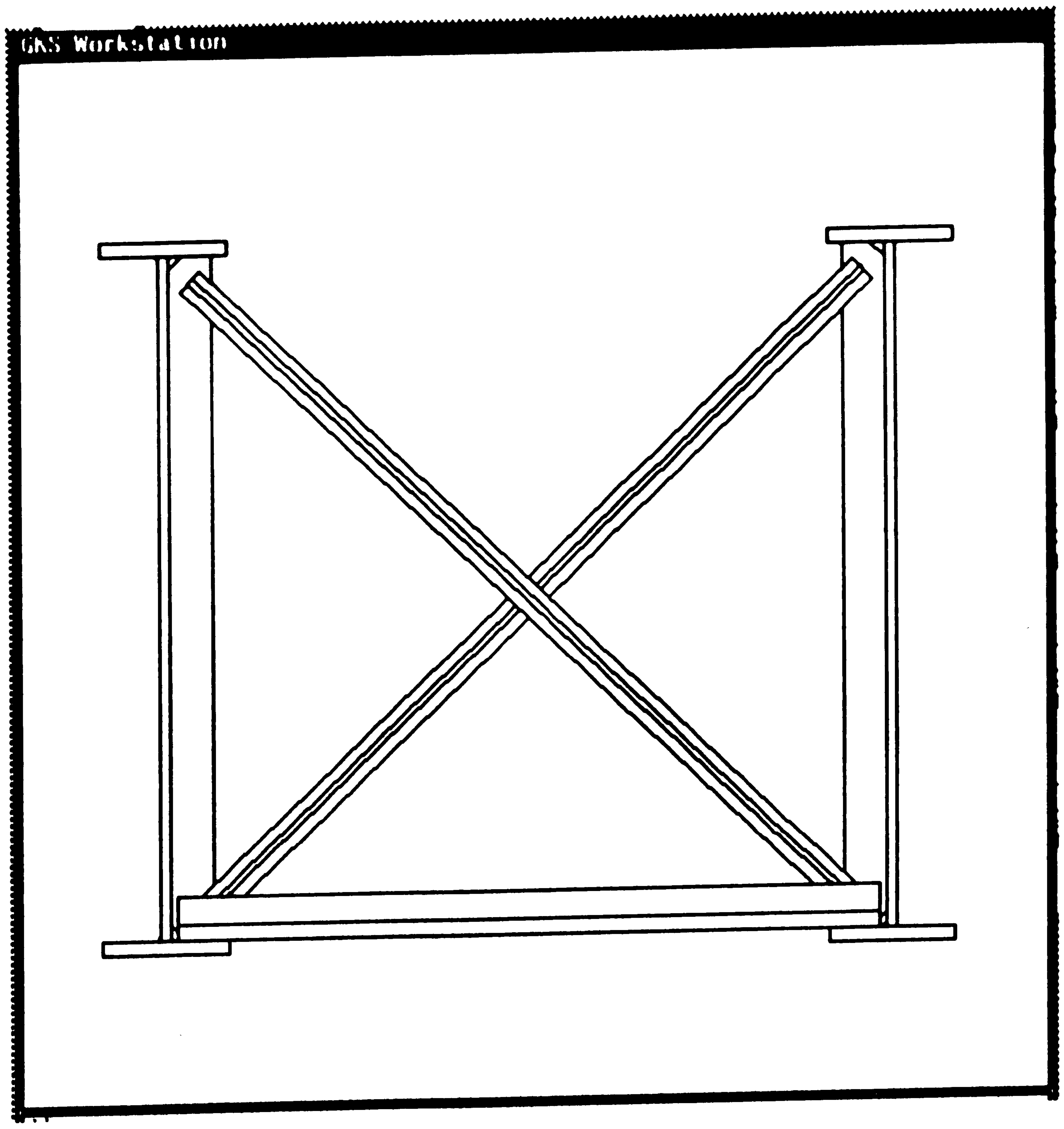
CONNECTION VIA FILLET OR
INTERMITTENT FILLET WELD

Fatigue problems are a possibility at the termination of these type of welds, or from imperfections in the weld, especially if the flaw or termination occurs where the primary stress is tensile. Longitudinal fillets have the greatest susceptibility to fatigue problems.

FDC - Recommendation:
RECOMMENDATION ON FILLET WELDING

Fillet welding is often a cheaper and more feasible alternative to bolting and is therefore often chosen. If possible, connections should be bolted for fatigue resistance, if however, fillet welding is chosen, proper welding procedures should be observed to prevent flaws in the weld. In addition, the weld should not be terminated in a tension region.

After the user has completed the preliminary qualitative design of details on the structure, he can view a display of a typical section, for each moment region, of the structure described. A cross-section of the Delaware River Bridge, provided by FDC, is shown below. It should be noted, that the section displayed is of a portion of the structure between two girders, not the entire cross-section. However, this display shows the details which are typical across the entire cross-section, and is, therefore, representative of the entire structure.



Cross-section Display Of
Delaware River Bridge Provided By FDC

Vita

Matthew A. Bunner was born in Washington, Pennsylvania, on August 22, 1966. The son of Allan and Mary Ann Bunner, he is the youngest of four children.

He received his Bachelor of Science Degree in Civil Engineering from Lehigh University in 1988, graduating with highest honors. While at Lehigh, he was inducted into Phi Beta Kappa, Tau Beta Pi, and Chi Epsilon, and served as Vice-President of the student chapter of the American Society of Civil Engineers.

Matthew remained at Lehigh for full-time graduate study, and completed his Master of Science in Civil Engineering in June 1990.